MECHANICAL DAMAGE TO CORN IN A PNEUMATIC CONVEYING SYSTEM

by 584

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INTRODUCTION

Harvesting by field shelling, artificial drying, and mechanical handling of corn on the way from producer to consumer, characterize the modern methods in a corn harvesting-handling system. All these processes have been charged with causing damage to grain.

Harvesting machinery may be responsible for most of the mechanical damage, and considerable effort has been devoted to improve the design of combine components and combine operation in order to minimize damage to corn during harvest. However, some corn is damaged during elevating, throwing, and pneumatic conveying (30).

During recent years, foreign buyers have been increasingly critical and concerned regarding the poor quality of U. S. grains and seeds. Much criticism of the poor quality is attributed to the substantial amount of broken kernels reported to be present when received by foreign buyers. The estimated average of corn screenings cleaned out before the grains get to the consumer is over three percent. These screenings are worth less than whole corn.

The pneumatic conveyor has several advantages over the mechanical conveyor for transporting grains; consequently, it is used in marketing channels. Complicated problems are involved in grain handling, since grain properties such as dryness, brittleness, texture, structure, and resilience must be taken into consideration to keep the breakage to a minimum during

handling operations.

Most of the investigations in the grain conveying field were to obtain fundamental knowledge of the flow mechanism necessary for proper design, selection, and specification in order to improve performance. Limited information on grain damage during pneumatic conveying has been reported for explaining the relation between the extent of damage especially in connection with seed viability and variables pertinent to the pneumatic system.

Realization was observed in the importance of introducing a new concept of grain damage that includes damage in terms of not only seed viability but also any loss of over all grain quality not limited to a specific use. This investigation has attempted to determine the mechanical damage caused by pneumatic conveying. It has classified the damage into several categories and has studied the effects of grain properties and operation conditions of the system on the extent of each damage component.

OBJECTIVES

The objectives of this investigation were to study the nature and extent of mechanical damage to corn made by pneumatic conveying. More specifically,

(1) To obtain comparative data of mechanical damage caused by several operating conditions of the pneumatic conveyor.

(2) To investigate the effect of corn kernel size and/or

shape and moisture content on the extent of mechanical damage for various operating conditions.

(3) To study the damage done by repeated runs with the same grain and operating conditions.

LITERATURE REVIEW

Transporting grains by pneumatic conveyors is not a new field of development. Work by H. Gasterstädt (12) probably started the references concerning pneumatic conveyors in modern engineering literature. He related pressure drops associated with flows of air and air-solid mixture through wheat and granular solids. His investigation showed linear relationship between the pressure drop and air-solid ratio. Because of the importance from the standpoint of designing a system the pressure drop in the conveying pipe was studied by numerous investigators such as Segler (25), Hariu and Molstad (13), Crane and Carleton (8), Michell (21), Vogt and White (26), and Cornish and Charity (6). They used different approaches, either theoretically or empirically, to correlate static pressure in the conveying pipe as a function of important factors such as material conveyed, pipe length and diameter, grain load, grain and air velocity and system arrangement. No one presented a sound correlation which encompassed all the factors for predicting pressure drops.

In conveying agronomic seeds, the grain velocity is important not only in getting floatation to move but also in avoiding severe impact occurring at high velocity. Many recent papers have focused attention on the study of particle velocity. Dallavalle (9) summarized and discussed the results of terminal particle velocity determined by various investigators. He presented equations for vertical and horizontal terminal velocity based on his experiments. For mixtures of particles

of irregular shapes and varying densities, Foley (11) proposed to use the terminal velocity of particles as a measure of particle characteristics rather than using calculated fictitious particle sizes based on Stokes law. Bilanski (3) investigated the terminal velocities of various seed grains, the range of which was 17.9 feet per second for alfalfa to 44.3 feet per second for soybeans. Henderson (15) suggested that in vertical transport of material the air rate would be that required to support material, or floatation velocity, of the granular material, plus the conveying rate of about 50 feet per second. Alden (1) recommended conveying air velocity ranges for various agronomic seeds, but gave no consideration to mechanical damage associated with air velocity. Segler (25) showed that the ratio of grain velocity and conveying air velocity was constant for wheat and in horizontal conveying it was higher than that in vertical conveying. His data indicated that grain velocity was about 36 percent of air velocity for horizontal conveying and 27 percent for vertical conveying. Cramp and Priestly (7) used the same method but obtained somewhat higher values for grain speed-up to nearly 50 percent of air velocity.

Gasterstädt (12) was the first to point out the occurence of damage to grain when it is conveyed with too high air velocity. However, he made no special investigations on this aspect. Segler (25) carried out extensive work to investigate the various factors involved in grain conveyance that might have an influence on the degree and extent of the damage. A most critical factor in determining whether or not damage will

occur was the conveying air velocity. His work with peas showed that the incidence of damage rose proportionately with the cube of air velocity in its range between 45 and 95 feet per second. Moisture content of grain was shown to be an equally critical factor. For peas, the breakage was 0.1 percent with 17.1 percent moisture content, but was 11.1 percent with 15.4 percent moisture content. Experiments with wheat at three different moisture contents showed that whereas there was little evidence of damage to wheat at 15.2 percent moisture content even at an air velocity of 130 feet per second, damp wheat (22.6% m.c.) and dry (10.3% m.c.) were badly damaged at this speed.

Segler (25) also pointed out the influence of material input on grain damage. The damage increases as the input decreases. It was assumed that the denser stream of material at the greater inputs acts in some way as a cushion against the pipe wall, or perhaps that the individual grains collide with the wall less frequently or less steeply at the greater inputs. Segler also assumed that the pipe diameter would affect the grain damage and tested his theory on peas, with conveying pipes having 1.8 and 10.8 inches diameter, but identical in length and arrangement. His results showed that grains were damaged more in the smaller pipe than in the larger one, but the extent of the damage was very small either way and not significant for practical purposes.

There were several investigations made to determine the effect of the pneumatic conveyor on seed viability. Metzer (20) investigated the extent of viability loss due to various

operating conditions of pneumatic conveyors. He tested sorghum seed, barley, corn and oats for three different conveying systems, the approximate conveying capacity of 4850 to 8500 pounds per hour, velocity range between 3000 and 4700 feet per minute, and the moisture range between 11 to 12 percent. His experiments showed that the conveyor had no significant effect on viability of barley, corn and oats (when germinated at optimum conditions) immediately after conveying or after a 9-month storage period. Corn conveyed five times in the horizontal-elbow system and planted in cold soil had lower seedling emergence than nonconveyed corn samples or than corn conveyed one time or three times. Mechanical injuries caused by the conveyor became evident in sorghum and corn only after a storage peroid or when seed was subjected to adverse growing conditions. Pearson and Sorenson (23) studied minimum air velocity for conveying and air velocity in which damage to germination of sorghum grain occurs. They also investigated the influence of moisture content on establishing safe range of air velocity.

Different methods of grain damage evaluation have been made for different demands. When grain is used for stock feed, damage to germination or chipped grains is inconsequential. With seed corn it is of course important that germination not be impaired, and breakage be avoided. To determine seed viability in connection with pneumatic conveying, the standard germination and cold soil emergence tests were used (20). Segler (25) used Luff's ammonia procedure to investigate husk damage of barley for malting purpose. Various other methods such as fat acidity,

glutamic acid decarboxylase, and triphenyl tetrozolium chloride are available to detect physiological change (5). The present official method for determining damage involves individual analyses by visual observation for various types of damaged kernels. This method is too tedious and time consuming and human judgment plays too important a part in the final results. The sieving method (27), that has been standardized as the U.S. Official Grain Standard, shows some broken kernels and foreign material but not all the damaged kernels. As yet, a definite method applicable to various damages of different grains has not been established. Thus, investigations are being conducted at Kansas State University (5) and elsewhere to find one or more properties which will serve as a damage index and to develop a method or device to determine quantitatively the percentage of sound grain in a sample so that the need for individual analyses for different types of damaged kernels can be eliminated.

Since only limited data on grain damage associated with handling equipment and various types of conveyors are available, investigations on this aspect are urgently needed for developing methods and devices to minimize grain damages.

EXPERIMENTAL METHOD

A. Equipment

The pneumatic conveying system used for the experimental work consisted of air blower, air-lock feeder, conveying pipe, cyclone separator, power unit, and various metering and pressure guages. This may be classified as the low-volume, medium pressure system. Photographs of the pneumatic conveying system and the schematic diagram of the component arrangement are shown in Figures 1 and 2.

A positive displacement air blower was used for supplying air into the system. The blower was specified to have a capacity of delivering air at the maximum pressure of 10 p.s.i.g. continuously, or 12 p.s.i.g. intermittently at the maximum temperature of 350 °F. The air intake filter was connected to the blower to prevent possible airborne impurities from entering the system and to subdue the noise generated by the blower. The amount of air intake could be regulated by changing blower speed.

The pressure relief valve was installed directly after the blower to prevent overloading. The inlet air temperature and pressure were measured before air passed through the rotameter in order that volumetric flow rate of air could be evaluated for different air temperatures. The rotameter, was calibrated at 100 °F and 2 p.s.i.g. pressure to measure 180 cubic feet of air flow per minute at the 100 percent reading.

The rotary drop-through air lock feeder was used to introduce

Plate 1.

Photograph of Pnuymatic
Conveying System used in
the Experiment.

grain into the system, thus, ensuring no excessive amounts of air loss from the system. A surge hopper was placed on top of the air lock feeder; the amount of grain fed was metered by the circular cone ofifice fitted in the hopper. A standard manifold for the drop-through air lock connected the air delivery and the grain transport line.

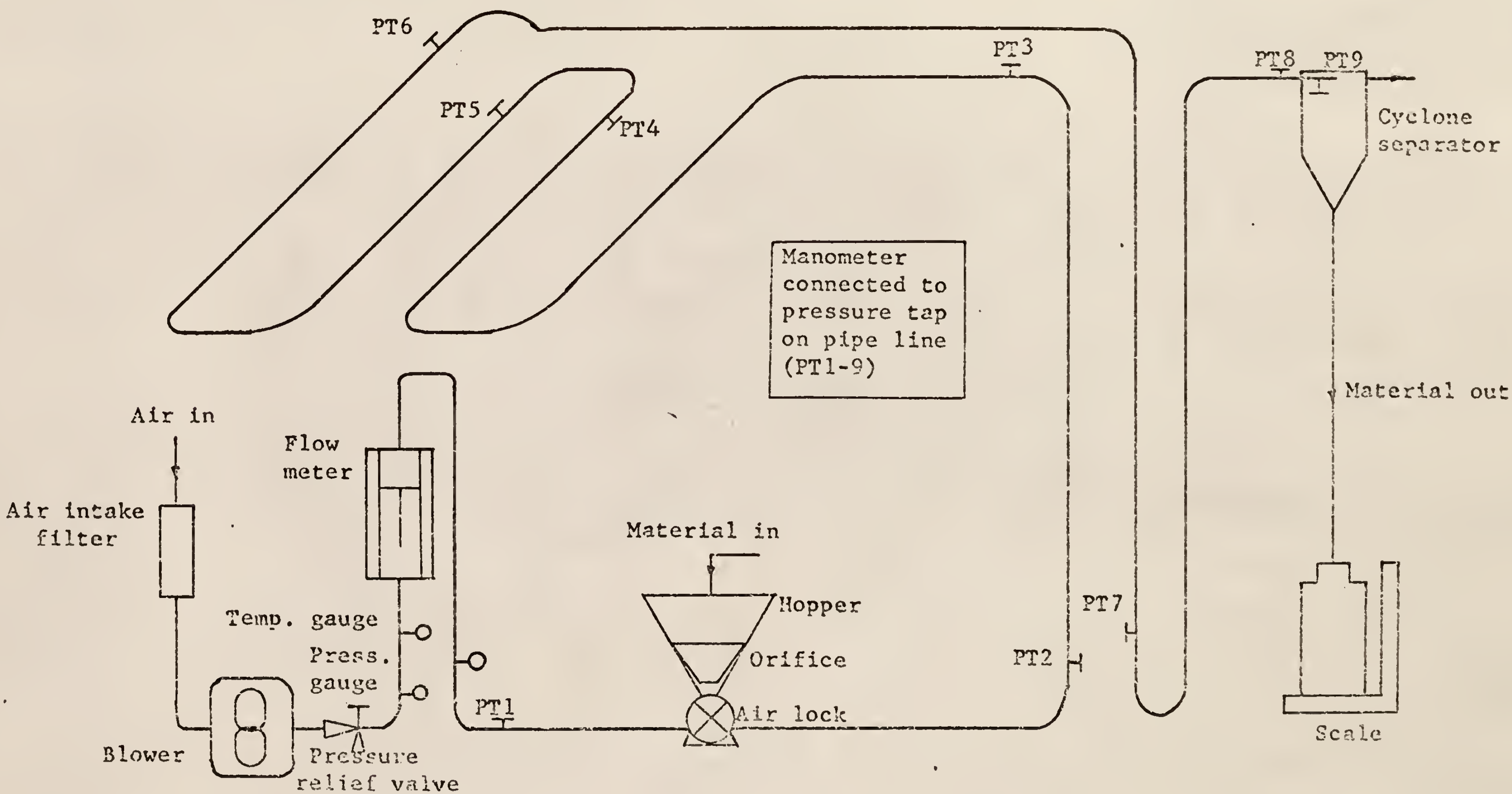
Total length of the transport line between the feeder and cyclone separator was 200 feet. The first and last portions of straight vertical lines were transparent pipe lines, through which the passing material could be seen. These were acrylic resin tubes, each being 6 feet 2 inches long and having an inside diameter of 1.9 inches. The remaining transport line was 1.9 inch I.D. aluminum pipe. The line contained 15 elbows, of which 14 were 90 degrees with 24-inch radius of curvature, and the other, 45 degrees with the same radius. Their length was equivalent to 45 feet 6 inches.

The pressure drops in the transport line could be measured through pressure taps located at various sections of the line. It was found later that only two taps, PT 1 and PT 2, as shown in Plate II, were necessary to carry out the purpose of the experiment. The static pressure of these two positions was recorded by the spiral element type pressure recorder.

Plate II

Schematic Diagram of Pneumatic Conveying System

Length of conveying line: 200'
Diameter of conveying pipe: 1.9" ID
Straight portion: Vertical --- 22'6"
Horizontal - 132'
Number of elbows: 14(90°- 24"R), 1(45°- 24"R)
Equivalent lenght: 45'6"


PT6
PT5
PT4
PT3
PT8
PT9
Cyclone separator
Manometer connected to pressure tap on pipe line (PT1-9)
Air in
Flow meter
Air intake filter
Material in
Hopper
Orifice
Air lock
Temp. gauge
Press. gauge
PT1
PT2
PT7
Material out
Scale
Blower
Pressure relief valve

B. Materials

Yellow corn harvested in 1967 and 1968 was used in this investigation to evaluate the mechanical damage caused by the pneumatic conveyor. Shelled corn of 1967 was taken from the chilled storage test bin after 150 days of refrigerated air treatment at the grain temperature of 35-40 $^{\circ}$F. The moisture content of the grain when taken from the bin was within the range of 11-13% wet basis. Shelled corn of 1968 was also taken from the chilled storage test bin after 4 weeks of treatment at the same temperature range. The moisture content of the corn was around 20%.

Shelled corn generally is composed of various kernel sizes and shapes, and its distribution may differ considerably according to the growing history and variety of grain. Because of prevailing differences in mechanical and aerodynamic properties of grain, distribution characteristics were considered to be significant in pneumatic conveying. By use of a corn grader, the corn was first sorted into eight uniform shapes and sizes: small medium flat, small small flat, large flat, large medium flat, large round, medium round, large kernel, and residue. Percent weight fraction belonging to each class is shown in Table 1. Some of the physical properties of the classified grain were measured and are shown in Table 2. Residue (#8) was composed of cracked corn and foreign material. Large kernels (#7) were an extremely small fraction, less than one percent, of the whole. Therefore, among the other six components, large medium (#5), small small flat (#2), the mixture of large round and medium

Table 1. Classification and distribution of test corn according to size and/or shape

Designation	#1	#2	#3	#4	#5	#6	#7	#8
Classification	Small medium flat	Small small flat	Large round	Large flat	Large medium flat	medium round	Large	Residue
Sieve opening (in.)	$\frac{11.5}{64}$-$\frac{12.5+}{64}$	$<\frac{11.5+}{64}$	$>\frac{14.5}{64}$	$\frac{12.5}{64}$-$\frac{14.5}{64}$	$<\frac{12.5}{64}$	$>\frac{12.5}{64}$	$>\frac{28}{64}$ (R)	$<\frac{17}{64}$ (R)
	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent
1967 corn								
Test 1	8.69	24.87	5.59	9.10	41.13	7.33	0.19	3.13
Test 2	9.26	24.08	5.70	8.50	39.30	8.84	0.60	4.10
Test 3	12.50	22.36	6.71	11.56	38.78	7.72	0.42	3.45
1968 corn								
Test 1	5.11	10.24	10.63	18.74	45.58	6.57	0.43	2.69
Test 2	5.11	8.99	9.91	23.33	42.82	6.33	0.43	3.08

Table 2.a. Some physical and mechanical properties of test corn according to size and/or shape

Designation	#1	#2	#3	#4	#5	#6
Classification	Small medium flat	Small small flat	Large round	Large flat	Large medium flat	Medium round
Volume per kernel* (cm^3) (12% moisture)	0.2284	0.2070	0.3109	0.2877	0.2607	0.2392
Weight per kernel (gr)* (12% moisture)	.2944	.2671	.4016	.3820	.3405	.3090
Compressive strength** (flat way) (12% moisture)	95.20	98.64	52.24	53.40	98.64	63.40
Compressive strength*** (flat way) (19.5-19.8% moisture)	---	106.50	70.02	---	93.33	76.60

* Average values of three replications
** Average values of 25 kernels
*** Average values of 50 kernels

Table 2.b. Mechanical damages to each classified corn before handling in pneumatic conveyor[1/]

Moisture Level / Damage / Size and/or shape	High moisture corn (20%)			Low moisture corn (12%)		
	Large cracks (%)	Small cracks (%)	Broken damage (%)	Large cracks (%)	Small cracks (%)	Broken damage (%)
Round shape corn	2.65	14.34	4.55	3.25	14.47	6.92
Large medium (flat) size	2.01	13.94	6.46	3.35	12.42	7.48
Small small (flat) size	0.59	14.85	13.28	2.16	10.99	10.15

1/ Average of six replications.

round (#3, #6)---the proportion being 4 to 6---were selected to be tested in the pneumatic conveyor system. Shelled corn kernels belonging to these three classes were of distinct shapes and/or sizes. Furthermore, the majority of corn samples, about 80%, fell into these classes. In this manner, a uniform sample in size and/or shape was obtained.

During harvesting and handling, corn kernels were damaged. Damages to the original samples for three classes selected were evaluated and are shown in Table 2.b.

C. Experimental Design

Four variables were studied to accomplish the objectives of this investigation: air velocity, number of repeated runs, moisture content, and size and/or shape of grain. Levels of each variable studied are summarized in Table 3. Even though the air velocities were designed as above, it might not be easy or convenient to obtain such desired velocities for all experiments, because some changes of temperature and air pressure in the system would cause the change in air velocity. As a convenient way, therefore, the appropriate rotameter readings corresponding to the desired air velocities, which are shown in parentheses in Table 3, were used to regulate air flow rate. The estimation of actual air velocities used for each treatment was obtained by using the equation of continuity with corrections due to pressure and temperature variations. The air velocities so obtained are shown later along with other experimental results.

The number of repeated runs, 1, 4, and 8 times in the design, are equivalent to the total conveyed length of 200, 800, and 1600 feet, respectively.

The selection of two moisture levels, one for dry and one for wet corn, was based on the assumption that shelled corn, having the approximate moisture contents designated, could be encountered frequently in practical pneumatic handling.

For the experimental desin, "factorial" design was used in which four levels of air velocity, three levels of the repeated run, three levels of size and/or shape, and two levels of moisture content were involved. Therefore, there were 72(4x3x3x2)

Table 3. Levels of Experimental Variables

Levels / Variables	1	2	3	4
Air velocity (fpm) 1/ (rotameter reading)	4200 (48%)	5500 (65%)	6300 (75%)	7600 (92%)
No. of repeated runs	1(200')	4(800')	8(1600')	--
Size and/or shape	small small flat (#2)	large medium flat (#5)	Round (misture of #3 & #6)	--
Moisture content	dry corn (about 12%)	wet corn (about 20%)	--	--

1/ Approximate values

treatment combinations for each replication. Two replications were made for each treatment combination.

D. Procedure

Seven pounds of sampled corn, prepared as explained in (B), were used initially for each test run. The grain's feeding head above the orifice was maintained fairly constant to assure a uniform charge into the system. As grain was introduced into the system, the pressure and temperature were raised while the rotameter readings were lowered. The degrees of change depended upon the system's operational conditions of air and grain feeding rates. To obtain information necessary in defining the operational conditions for a given run, the air pressure, air temperature, and rotameter readings were recorded before and after introducing grain into the system.

A sample divider was used to evaluate damage of nearly 300 grams of grain treated in the pneumatic system. The remainder of the corn sample was put through a dockage tester which separated all other matter remaining on the sieve after screening. The portion that passed through the dockage tester screens was weighed and along with the total weight was used to evaluate percent of dockage. The same procedure was followed for every combination of predetermined levels of four variables investigated: air velocity, moisture content, size and/or shape, and the repeated runs.

The mechanical damage was classified into three categories: broken damage, large cracks, and small cracks. The standard for these classifications was established arbitrarily and defined as follows:

broken damage--any kernel that was chipped or broken

large cracks---cracks extending through the whole kernel

small cracks--any mark of skin damage other than the large cracks

To facilitate the damage evaluation, corn was first treated with green dye so that any chip or crack in the kernel could be seen easily. The dye-test was an effective visual aid in distinguishing the damaged kernel from the sound one. Sound kernels and those classified by the dye-test were weighed and the percentage of each class of damage was calculated.

To estimate the grain velocity in the conveying pipe, a series of conveying tests were carried out. A stop watch was used to measure the time required for the front mass of moving grain to pass from the upper section of the first transparent line to the upper section of the last transparent line. Before the end of this test the time required for the last mass of moving grain to appear in the same sections of the transparent line was measured also. Since the distance between these two sections was known, the average velocity could be obtained by dividing the known length of pipe by time required.

In this investigation, the feeding rate was regulated by an orifice; thus, only the time required for a given amount of the sample to enter the air lock needed to be measured in order to obtain the feeding rate.

SYSTEM ANALYSIS

Air velocity in the conveying pipe was known to be important and could become the most important factor in connection with mechanical damage of grain conveyed. Because of leakage through the air lock feeder, turbulence of stream line due to bends along the pipe line, and velocity variation in axial direction of pipe, it may not be easy always to estimate accurately the air velocity for a given air input into the system. Based on measurements and some principles of fluid mechanics, however, the average air velocity in the duct can be calculated approximately.

As mentioned earlier, the air flow rates in the pneumatic conveyor system were measured and regulated by rotameter readings. Since the rotameter is located between the blower and air lock feeder, air loss through the feeder must be estimated first. To estimate the air loss, the static pressures from two different positions on the pipe line were recorded for various rates of air flow with each air lock feeder sealed and unsealed. The pressure taps were located before and after the feeder as shown in Plate II.

The ralationships between the rotameter readings and the static pressures with feeder both sealed and unsealed were shown in Table 4. It was found that the ratameter reading was directly proportional to the square root of static pressure as shown in Plate III. The regression analyses were performed to relate these variables to give.

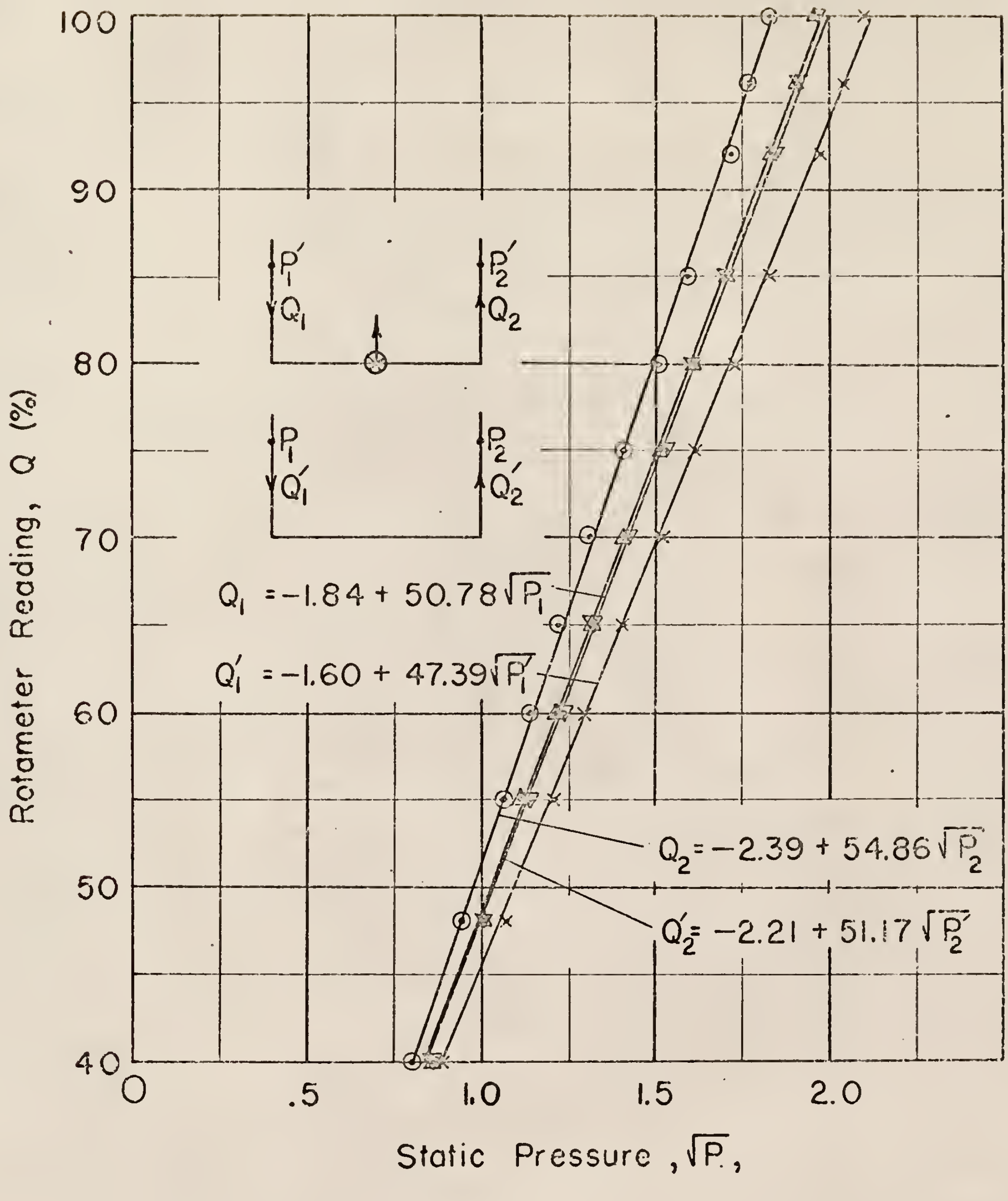
Table 4. The static pressures [1/], psig, for various rotameter readings with feeder sealed and unsealed

Rotameter reading (%)	With feeder sealed		Without feeder sealed	
	P_1	P_2	P_1	P_2
100	4.42	3.85	3.98	3.36
96	4.20	3.62	3.65	3.16
92	3.92	3.38	3.42	2.96
85	3.36	2.90	2.93	2.53
80	3.00	2.60	2.60	2.27
75	2.61	2.28	2.31	2.00
70	2.31	2.00	2.02	1.75
65	2.00	1.74	1.74	1.51
60	1.70	1.49	1.51	1.31
55	1.47	1.28	1.30	1.14
48	1.14	1.00	1.00	0.89
40	0.80	0.74	0.71	0.65

1/ The average values of two measurements recorded on the spiral element type pressure redorder.

Plate III

Plot of rotameter reading versus static pressures measured to estimate air loss through air-lock feeder.


P_1'
Q_1
P_2'
Q_2
P_1
Q_1'
P_2
Q_2'
$Q_1 = -1.84 + 50.78\sqrt{P_1}$
$Q_1' = -1.60 + 47.39\sqrt{P_1'}$
$Q_2 = -2.39 + 54.86\sqrt{P_2}$
$Q_2' = -2.21 + 51.17\sqrt{P_2'}$
Rotameter Reading, Q (%)
100
90
80
70
60
50
40
0
.5
1.0
1.5
2.0
Static Pressure, $\sqrt{P}$,

$$Q_1 = -1.84 + 50.78\sqrt{P_1} \tag{1}$$

$$Q_1' = -1.60 + 47.39\sqrt{P_1'} \tag{2}$$

$$Q_2 = -2.39 + 54.86\sqrt{P_2} \tag{3}$$

$$Q_2' = -2.12 + 51.17\sqrt{P_2'} \tag{4}$$

where Q_1 and Q_1' are air volume flow rates (rotameter readings in percent) as the feeder was sealed and unsealed, respectively. P_1 and P_1' are corresponding static pressure measurements at tap I. The subscript 2 indicates the case at tap II.

For a given flow rate, the pressure differences at two positions, taps I and II, when the feeder was sealed and unsealed, could be caused by air loss through the feeder. Since Q is proportional to the square root of P, the flow rate difference at the rotameter for a given pressure could be considered as the air loss through the air lock feeder. Therefore, two estimations could be made for air loss through the feeder by comparing two pairs of equations, (1) and (2), and (3) and (4), which are,

$$A_1 = \frac{Q_1' - Q_1}{Q_1'} \times 100 \tag{5}$$

$$A_2 = \frac{Q_2' - Q_2}{Q_2'} \times 100 \tag{6}$$

where A_1 and A_2 are percent air losses (volume basis) through the feeder estimated by static pressure measurements at tap I and tap II, respectively.

The air loss estimated by equation (5) was reduced slightly by increasing airflow rate. The range of loss was 6.40 - 6.56

percent for the rotameter range of 40 - 100%. On the other hand, the air loss estimated by equation (6) was within the range of 6.48 - 6.62 for the same range of flow rate. The difference between the two estimations was 0.22% at maximum. Therefore, the average value of 6.52 air loss was selected for the entire range of air rates used in the pneumatic conveyor system. Air temperature and pressure in the conveyor pipe during the operation, depended upon the atmospheric conditions and the airflow rate into the system. Since the rotameter has been calibrated at the pressure of 2 p.s.i.g. and temperature of 100°F, the flow rate other than that of the calibrated conditions should be corrected for the conditions that were actually encountered.

For the duration of operating the system, air temperature for a given airflow rate was found to be quite different from the atmospheric temperature. Therefore, corrections were obtained for the wide range of temperature change that might be expected during actual operation of the system. On the other hand, pressure changes were practically negligible for actual range of temperatures in a given flow rate of air. Hence, the pressure corrections were made only for different airflow rates by taking the atmospheric pressure, 14.7 p.s.i.a., as the standard.

The correction factors[1/] for temperature and pressure are presented in Table 5 along with the average air velocities in the conveying pipe. It should be noted that the air velocities in

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1/ Correction factor curves for Flowrator meters, Fischer & Porter Co., Warminster, Pennsylvania.

Table 5. The average air velocities in the conveyor pipe corrected for temperature and pressure (ft/sec.).

Air rate at rotameter %	Static pressure psig 1/	Pressure correction	Temperature (°F) and temperature correction									
			80	90	100	110	120	130	140	150	160	170
			1.02	1.011	1.00	0.993	0.984	0.975	0.967	0.959		
40	1.172	.970	63.28	63.85	64.55	65.01	65.61	66.20				
48	2.266	.995	74.03	74.69	75.51	76.05	76.74	77.45	78.09			
55	2.750	1.02	82.75	83.51	84.41	84.99	85.78	86.57	87.29	88.01		
60	3.110	1.03		90.20	91.18	91.83	92.67	93.52	94.30	95.08		
65	3.500	1.04		96.77	97.83	98.53	99.42	100.34	101.17	102.01	102.76	
70	3.844	1.05			104.36	105.09	106.03	107.03	107.91	108.81	109.62	
75	4.110	1.06			110.76	111.53	112.56	113.60	114.54	115.49	116.35	
80	4.853	1.08				116.77	117.84	118.92	119.90	120.91	121.79	
85	5.469	1.10				121.81	122.92	124.06	125.09	126.13	127.06	128.13
92	6.328	1.13					129.52	130.71	131.79	132.45	133.85	135.01
96	6.797	1.14						135.20	136.31	137.45	138.46	139.63
100	7.250	1.15							140.77	141.93	142.98	144.19

1/ Average of three mesurements.

Plate IV

Average air velocity in the conveying pipe of conveying system used in this experiment.

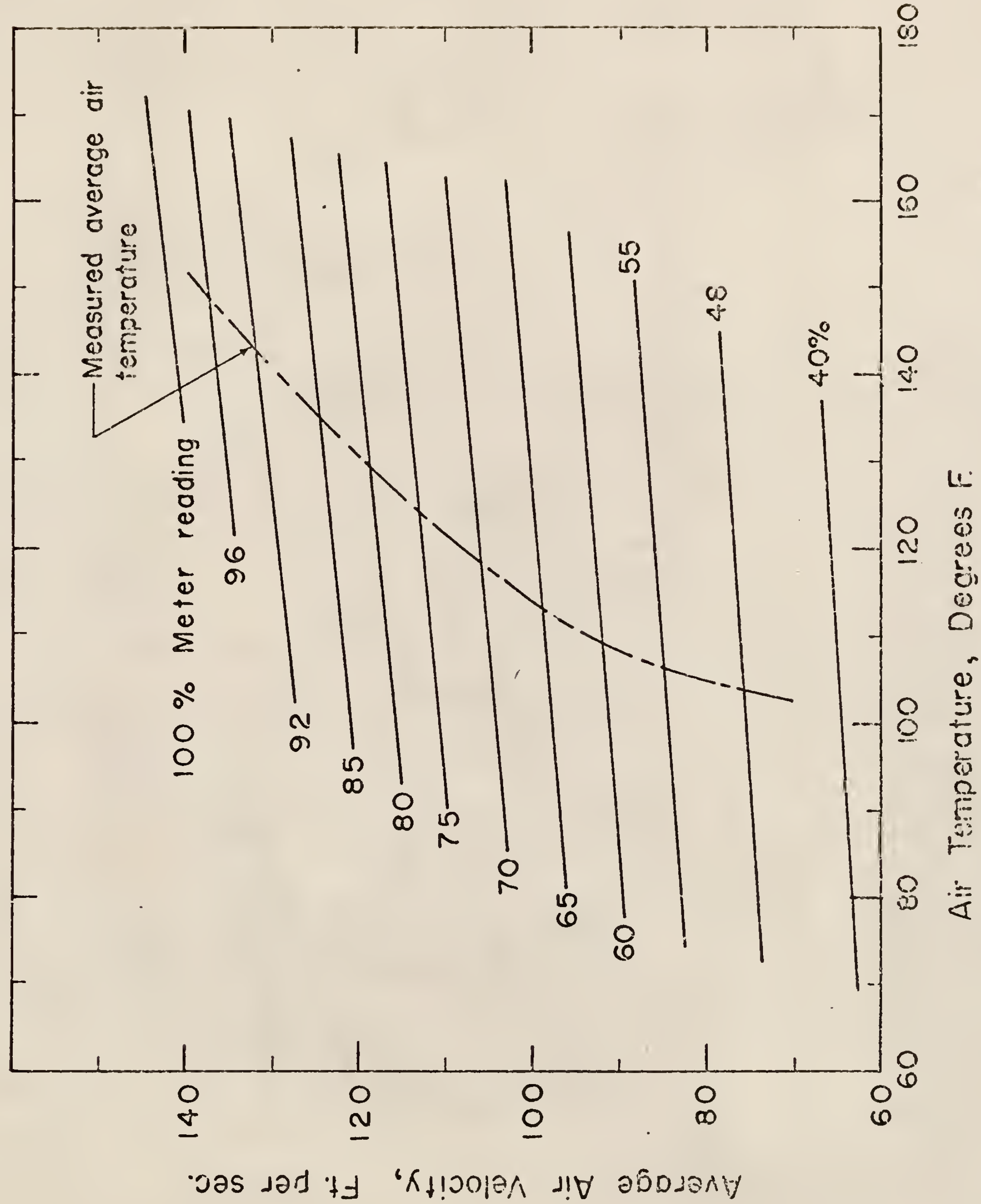
Measured average air temperature
100 % Meter reading
96
92
85
80
75
70
65
60
55
48
40%
Air Temperature, Degrees F.
Average Air Velocity, Ft. per sec.
60
80
100
120
140
160
180
60
80
100
120
140

Table 5 have been corrected for temperature and pressure, but that air loss through the air lock feeder has not been accounted for. Figure 4 shows the average air velocities corresponding to rotameter readings at various temperatures.

When grain was introduced through the feeder, the volume rate of air was reduced to a certain rate until the steady state was obtained. The reductions in flow rate due to grain introduced were 4.5 ± 0.5, 5.5 ± 0.5, 5.5 ± 0.5 and 6.5 ± 0.5 percent for 48, 65, 75, and 92 percent of the original rotameter setting, respectively. Therefore, the actual air velocity in the conveying line as grain is fed into it should be based on the reduced volume rate.

Since the pneumatic system in this investigation was composed of vertical and horizontal pipe lines with many elbows, the grain velocity is different from one point to another. Therefore, the average grain speed is more meaningful than the velocity at a specific point. The average grain speeds, obtained by the method as explained earlier, for different corn size and/or shapes are summerized in Table 6.

Except for the conveying air velocity of 66 feet per second, it may be noted that these average grain speeds were higher than Bilanski's published terminal velocity of 34.9 feet per second. For this air velocity, it was observed that a small portion of conveying corn settled down in the conveying pipe.

The measured feeding rates in pounds per minute used throughout all the experiments are also shown in Table 6.

Table 6. The average corn speed in fps. and feeding rate in the pneumatic conveyor*/.

Corn size and/or shape	Air velocity at (ft. per second) 66	86	100	120	Feeding rate (Lbs./min.)
Round shape	28.24	39.97	48.29	60.10	26.49
Small small flat size	28.42	39.05	50.17	58.48	26.85
Large medium flat size	27.24	40.28	44.72	54.90	26.25

* Average of three measurements

ANALYSIS OF GRAIN DAMAGE

The results of mechanical damage evaluated by the dye test and dockage tester are shown in Tables 7 through 12 in Appendix I. In these tables the total damage in percent is the percent sum of the broken, large, and small cracks.

Since some damaged grains would usually be present before the grain was ever conveyed, the devaluation number can be used as an index for expressing the extent of mechanical damage caused by pneumatic conveying. The devaluation number E in percent is defined as follows:

$$E = \left[1 - \frac{D_i}{D_o}\right] \times 100 \tag{7}$$

where D_o is the percent fraction of sound grains before conveying in the system,

D_i is the percent fraction of sound grains after passing i times in the pneumatic system, i being the number of the repeated run.

The devaluation numbers based on total damage were calculated and shown along with the other damage data in Table 7 through 12 in Appendix I.

A. Statistical Analysis

Statistical analysis of the factorial experiments in this investigation was performed with data from each classification of grain damage. As mentioned earlier, factors studied were conveying air velocity (V), total pipe length for grains conveyed

(L), and grain size and/or shape (S). The mathematical model used for the analysis was

$$X_{ijkl} = \mu + S_i + V_j + L_k + (SV)_{ij} + (SL)_{ik} + (VL)_j + (SVL)_{ijk} + E_{ijkl} \qquad (8)$$

where X_{ijkl} = a sample corn damage with ith size and/or shape, j air velocity, and k conveying length;

μ = the grand average of all X_{ijkl} conceivable for the specific corn size and/or shape, air velocity, and conveying length;

S_i = the true average effect of i treatment of size and/or shape relative to μ, with the specific air velocity and conveying length. Hence, $\sum_{i=1}^{i} (S_i) = 0$ and the expected value of S_i, $E(S_i)$, is equal to S_i;

V_j = the true average effect of j treatment of air velocity, with the specific size and/or shape and conveying length. Hence, $\sum_{j=1}^{j} (V_j) = 0$ and $E(V_j) = V_j$

L_k = the true average effect of k treatment of the conveying length relative to μ, with the specific size and/or shape and air velocity. Hence, $\sum_{k=1}^{k} (L_k) = 0$ and $E(L_k) = L_k$

$(SV)_{ij}$ = the true average effect of combining i level of size and/or shape and j level of air velocity treatment relative to μ, with the specific conveying lengths. Hence,

$$\sum_{i=1}^{i}\left[(SV)_{ij}\right] = \sum_{j=1}^{j}\left[(SV)_{ij}\right] = \sum_{i=1}^{i}\sum_{j=1}^{j}\left[(SV)_{ij}\right] = 0$$

$(SL)_{ik}$ = the true average effect of combining i level of sizes and/or shapes and k level of conveying lengths relative to μ, with the specific air velocities. Hence,

$$\sum_{i=1}^{i}\left[(SL)_{ik}\right] = \sum_{k=1}^{k}\left[(SL)_{ik}\right] = \sum_{i=1}^{i}\sum_{k=1}^{k}\left[(SL)_{ik}\right] = 0$$

$(VL)_{ik}$ = the true average effect of combining j levels of air velocities and k level of conveying lengths relative to μ, with these specific sizes and/or shapes. Hence,

$$\sum_{j=1}^{j}\left[(VL)_{ik}\right] = \sum_{k=1}^{k}\left[(VL)_{jk}\right] = \sum_{j=1}^{j}\sum_{k=1}^{k}\left[(VL)_{jk}\right] = 0$$

$(SVL)_{ijk}$ = the true average effect of combining all three factors for their specific ijk combination. Hence,

$$\sum_{ijk}\sum\sum\left[(SVL)_{ijk}\right] = 0$$

E_{ijkl} = the random error of damage evaluation associated with the l damage data within the i size and/or shape, j air velocity and k conveying length. It is assumed that the E_{ijkl} are normally independently distributed variates, or NID(0, σ^2).

Tables 13 through 20 in Appendix II show the analysis of variance for dockages, small cracks, broken damage, and the devaluation

numbers. The "F" distribution furnishes the decision whether a hypothesis would be accepted or rejected. The following hypotheses were tested against althernative hypotheses, for each component effect of the factors involved within a classification of grain damage:

(a). Hypothesis $H_o[\mu_{r1} = \mu_{r2}]$ against the alternative hypothesis $H_a[\mu_{r1} \neq \mu_{r2}]$ where μ_{r1} and μ_{r2} are means of observations in replication 1 and replication 2, respectively.

(b) H_o (all the treatment effects are the same) against H_a (some treatments are not the same)

(c) H_o (all $S_i = 0$) against the alternate hypothesis H_a (some $S_i \neq 0$)

(d) H_o (all $V_j = 0$) against H_a (some $V_j \neq 0$)

(e) H_o (all $L_k = 0$) against H_a (some $L_k \neq 0$)

(f) H_o all $(SV)_{ij} = 0$ against H_a some $(SV)_{ij} \neq 0$

(g) H_o all $(SL)_{ik} = 0$ against H_a some $(SL)_{ik} \neq 0$

(h) H_o all $(VL)_{jk} = 0$ against H_a some $(VL)_{ik} \neq 0$

(i) H_o all $(SVL)_{ijk} = 0$ against H_a some $(SVL)_{ijk} \neq 0$

B. Results of Analysis

(1). The broken damage of corn at lower moisture level (12%).

(a) $H_o[\mu_{r1} = \mu_{r2}]$ is accepted over $H_a[\mu_{r1} \neq \mu_{r2}]$ because $F(1, 35) = 0.046$ is much less than $F_{.05}(1, 35) = 4.12$

(b) H_o (all treatment effects are the same) is rejected in favor of

H_a (some treatment effects are not the same), for $F(35,35) = 280.69 >>> F_{.05}(35,35) = 2.25$.

(c) H_o (all $S_i = 0$) is rejected in favor of H_a (some $S_i \neq 0$), for $F(2,35) = 16.13$, $F_{.01}(2,35) = 5.29$.

(d,e) In a similar way, H_o (all $V_j = 0$) and H_o (all $L_k = 0$) are rejected in favor of H_a (some $V_j \neq 0$) and H_a (some $L_k \neq 0$) by comparing their observed F values with the corresponding values of "F" distribution at $\alpha = 0.01$.

(f,g,h) With respect to the first order interations, H_o [all $(SV)_{ij} = 0$] and H_o [all $(SL)_{ik} = 0$] are rejected over

H_a some $(SV)_{ij} \neq 0$ and H_a some $(SL)_{ik} \neq 0$. On the other hand, H_o all $(VL)_{jk} = 0$ is rejected in favor of H_a some $(VL)_{jk} \neq 0$.

(i) For the second order interaction, H_o [all $(SVL)_{ijk} = 0$] is accepted over H_a [some $(SVL)_{ijk} \neq 0$].

It may be concluded from the results of (a) above that there were no differences between the two replication means for broken damage, in other words, that very reliable data for broken damage were obtained. From the results of testing hypothesis from (b) to (i), the conclusion may be drawn that on the broken damage there were very significant effects of air velocity, conveying pipe length, and the combined air velocity and conveying length. Size and/or shape was also a significant factor statistically, but may not be as important as other significant factors.

The results of hypothesis tests from (a) to (i) were summarized in the "F" column in Table 15 in Appendix II. To avoid an unnecessary duplication, only the conclusion for analysis results of each kind of grain damage component will be presented.

(2). The broken damage at higher moisture (about 20%).

For higher moisture corn as shown in Table 16 in Appendix II, the same factors as those for lower moisture corn have the significant effects but the order is changed. In this case the size and/or shape effect was the most important factor followed by conveying length, velocity, and the combined effect of conveying length and velocity.

(3). The small cracks.

As seen in Tables 13 and 14 in Appendix, three main factors and VXL interaction were significant effects on producing the small cracks for either moisture level of corn but with order. Air velocities were the most pronounced effects for both moistures. Size and/or shape effect for lower moisture level

was more significant than the one for higher moisture level.

(4). Devaluation number.

For either moisture level there were highly significant effects from air velocity and conveying length, and there were significant effects of size and/or shape, and velocity and conveying length. The components of variances for high moisture level were generally smaller than the corresponding components for low moisture level. The size and/or shape effect was much more pronounced for low moisture content corn than was the VXL interaction; this effect was reversed in high moisture level.

(5). Dockage

It appeared that dockage data may not follow normal distribution. In order to ensure the normality, dockage data was transformed into Arcsin angular values before performing an analysis. The results are shown in Tables 17 and 18 in Appendix II.

For either moistue level, 12 or 20 percent, the test of hypothesis showed no difference between replications. For high moisture corn, the size and/or shape factor was the most significant, followed by conveying length, air velocity, and their three first order interactions. On the other hand, for low moisture corn the effects of air velocity and conveying length were so significant that the size and/or shape factor and the interactions related to it were practically negligible even though they showed statistically significant.

DISCUSSION OF RESULTS

It has been shown statistically what factors and interactions of factors had significant effects on causing each category of mechanical damage during pneumatic conveying. Mostly, air velocity followed by conveying length was so significant that the other effects were too small to compare. However, there was an exception where size and/or shape factor was the most important among all the effects considered. The direction and relative importance of effects of factors investigated follows.

As a part of total damage, the large cracks, not analyzed statistically, showed not only small percentage but also little response to the change of factors. Rather, it would be included in the classification of small cracks, naming the small and large cracks all together as "cracks".

The small cracks were generally increased with air velocity and conveying length for either moisture level, regardless of size and/or shape of kernel, as seen in Figures 5 through 7. in Appendix III. However, an exception occurred at the highest air velocity, about 120 feet per second, in which the small cracks for low moisture corn were rapidly decreased after four repeated runs or 800 feet conveying. Such a decrease of small cracks was directly related to the increase of broken kernels. For higher air velocities, usually above 100 feet per second, the difference in small cracks between high and low moisture corn tended to increase, while at low air velocities (about 60 to 86 feet per second) the difference was very small.

The broken damage also was increased with air velocity and conveying length for either moisture level and different grain size and/or shapes, as seen in Figures 8 through 10 in Appendix III. For higher moisture level, the broken damage caused during pneumatic conveying was less than 10 percent even at the highest air velocity and longest conveying distance studied. On the other hand, at low moisture level, the response of the broken damage was so acute that about 70 percent of the grain samples at the extreme operating condition belonged to this damage category.

Dockage was the only damage evaluation that was not involved in human judgment for classifying damages. Therefore, it should be considered to be the most consistent and reliable data. The effects of air velocity and conveying length for different moisture levels are shown in Figures 11 through 13 in Appendix III. Dockage increased very rapidly with air velocity and conveying length, especially in low moisture level. For low moisture level, dockage for the round shape was the most and dockage for large medium (flat) size was the least for each comparable treatment. However, for high moisture level, the small small (flat) size had a greater amount of dockage than the other two materials. This may result from the larger amount of damage in original small small (flat) size samples compared to the other two materials.

Devaluation numbers as an index of total damage caused during pneumatic conveying were compared for different air velocities, conveying length, and moisture level. The results are shown in Figures 14 through 19 in Appendix III. Total

damage at lower moisture content was much higher than that at high moisture level for each corresponding operation condition. At high moisture level, the devaluation number could be kept below 30 percent even for the highest air velocity of 120 feet per second and the longest conveying distance of 1600 feet, while devaluation numbers of low moisture corn were far beyond this range for 100 feet per second of air velocity and 800 feet of conveyance.

By statistical analysis, size and/or shape were shown to have effects on the extent of devaluation number. As the devaluation numbers were compared with three different size and/or shape factors for each corresponding operation condition, the order of magnitude of devaluation number was from the highest, round shape, large medium (flat), and small small (flat) size, the latter two of which were nearly the same.

It is interesting to compare the extent of devaluation number with the static compressive strength of kernels as shown in Table 3. Kernels at high moisture level showed higher strength than ones in low moisture for each corresponding size and/or shape. The strengths of small small size and large medium size were nearly the same, but were higher than those of round shape kernels for a given moisture content of corn. These results indicated that the devaluation numbers varied the same direction as the results of static compression tests, even though two cases were subjected to different kinds of forces causing grain damage.

Because of practical importance, an attempt was made to

work out the relation between devaluation number and dockage. If so, the total damage or devaluation number can be predicted from dockage test. However, the devaluation number for a given dockage varied so widely that, perhaps, reasonable prediction would not be well obtained, as seen in Figure 1 in Appendix III Instead, the broken kernels, as the most critically damaged, were plotted against dockage for all treatment combination factors studied. The result is shown in Figure 2 in Appendix III. The broken versus dockage relation showed two distinct trends. For less than about four percent of dockage, the general trend of the broken increased at low rate with dockage, the most of the brokens within this limit being less than 20 percent. However, the broken damage increased rapidly with further increase of dockage. This may be the case when the pneumatic conveyor was operated with higher air velocity and with long distance of grain conveyance. Deleting those points belonging to about four percent of dickage, the regression analysis was performed to give

$$B = 12.85 + 2.88 \log D \qquad (9)$$

where B = the estimated broken damage in percent

D = the dockage or the broken damage, in percent, that passed through No. 12 sieves in dockage machine, where $0.05 < D < 4\%$

95 percent confidence band for equation (9) was shown in Figure 2 in Appendix III. The broken, B', for the dockage larger than 4%, D', was related by the equation

$$B' = -18.49 + 29.23 \log D' \tag{10}$$

For discussing grain damage, it is desirable to refer to the U.S. Grade requirements of corn in terms of the results of this investigation. As grade standard in reference to mechanical damage, No. 12 sieve (12/64-inch round hole) was used to order to separate the cracked corn and foreign material which corresponds to the dockage classification in this investigation. For instance the maximum limits of cracked corn and foreign material allowable is two percent in Grade 1, three percent in Grade 2 and four percent in Grade 3 (27).

The present grain grading standard would not indicate the extent of total damage in the whole sample because, as seen in this investigation, portion of the sample, not passed through No. 12 sieve, contained a large amount of damaged kernels, and the correlation between dockage and devaluation number was poor. However, if only broken kernels are to be considered in evaluating grain damage, a fairly good indication of grain damage can be made by the present grain grading standard which could be explained by equation (9).

To obtain information on damage-causing mechanisms pertaining to pneumatic corn conveying, the graphical differentiations were performed on devaluation number versus conveying length curves in Figure 16 in Appendix III and devaluation number versus air velocity in Figure 19 in Appendix III. The results were shown in Figures 3 and 4 in Appendix III. The same curves for different materials were not shown here because of having almost the same characteristics.

In reference to Figure 3 , for a given moisture content the average damage rate with respect to the conveying length was generally very high in the first stage of conveying but decreased rapidly as the length increased. Such a high rate of damage in the initial stage may account for the fact that the large amounts of small cracks were caused at the very initial stage of conveying and that probably quite a large portion of small cracks merely enlarged the mark or image of skin damages without affecting much their proportion. This fact could be explained by the curves in Figures 5, 6, and 7 in Appendix III, in which the small cracks were very high in the initial stage of conveying.

In reference to Figure 4 in Appendix III, the corresponding curves for two different moisture levels revealed a difference in damaging characteristics. For high moisture corn, the damaging rate with respect to air velocity has almost the same pattern regardless of conveying length. The value of $\frac{dD}{dv}$ for a given air velocity was of course high for longer conveying length and $\frac{dD}{dv}$ value even for high air velocity was comparatively low. Therefore, the successive handling of high moisture corn with a pneumatic conveyor can be made with even the highest air velocity studied (120 ft/sec) without causing excessive damage. On the other hand, such trend for low moisture corn was shown only at relatively low air velocity, and there was an extreme value for each curve where $\frac{dD}{dv}$ changes sharply. It may be important to note that air velocity should be kept below that which gives such an extreme value of $\frac{dD}{dv}$ to avoid severe increase of damage.

The analysis available in this investigation shows that around 90 feet per second could be used generally as the upper limit of conveying air velocity which was obtained on the basis of $\frac{dD}{dv}$ versus air velocity curves. For this air velocity, the damaging rates with respect to air velocity were almost the same values regardless of conveying length and/or may be reasonably low enough to avoid the extreme value of $\frac{dD}{dv}$. It may be noted the proposed limit of air velocity, 90 feet per second or 5400 feet per minute, belongs to the lower limit of Alden's recommended range (1) of conveying air velocity, 5000-7000 feet per minute. His range may be too high to avoid the most critical rate of total damage for low moisture corn.

In concluding this section, the following illustrations for the application of the developed correlations and results are demonstrated:

(1) In a pneumatic corn conveying, one wishes to know the percent of the broken damage expected if dockage was three percent after conveying a dockage free corn. Then, from equation (9) or Figure 2, the broken damage can be estimated to be 16 percent.

(2) In operating a system similar to the one used in this investigation one could choose an appropriate operation condition within a certain limit of damage allowable shown in the results of this investigation. The following table shows the limit of operating conditions for conveying a dockage free corn so that a certain grade requirement could be satisfied after conveying.

Grade	Maximum allowable dockage (%)	High moisture (20%) Conveying length (ft)	High moisture (20%) air velocity (fps)	Low moisture (12%) conveying length (ft)	Low moisture (12%) air velocity (fps)
1	2	>1600	120	< 200	120
		>1600	100	< 400	100
		>1600	100	<1400	86
		>1600	100	>1600	66
2	3	>1600	120	< 300	120
		>1600	100	< 700	100
		>1600	86	<1600	86
		>1600	66	>1600	66

(3) If the total damage is more important, as may be a case for a specific use, the appropriate operating condition could be chosen within a certain limit of total damage caused during the pneumatic corn conveying as follows:

Total damage allowable (%)	High moisture Conveying length (ft)	High moisture air velocity (fps)	Low moisture conveying length (ft)	Low moisture air velocity (fps)
10	< 100	120	*	120
	< 600	100	*	100
	< 800	86	< 100	86
	<1400	66	< 400	66
20	<1200	120	*	120
	>1600	100	< 100	100
	>1600	86	< 600	86
	>1600	66	<1600	66

* Not to be conveyed.

The discussion has shown how air velocity was critical to the corn damage in pneumatic conveying. In addition, it should be noted that power consumption rises roughly with the cubed air velocity (25). Therefore, the lowest possible air velocity is

desirable not only to minimize grain damage for conveyor handling of grain, but also to minimize the cost of power operation.

CONCLUSIONS

The following conclusions were drawn from the results of this investigation:

(1) Air velocity, cinveying length, moisture content, and size and/or shape of corn had a significant effect on causing the broken, small crack, dockage, and devaluation number as an index of total damage. The most sifnificant factor was the air velocity, followed, in most cases, by the conveying length.

(2) Small cracks generally increased with increased air velocity and conveying length regardless of moisture and size and/or shape of kernels except with very high air velocity and longer conveying length. In that case a large portion of small cracks contributed to increasing breakage of corn kernels.

(3) The most significant factor causing the broken damage and dockage was the air velocity with conveying length next in significance. The equations relating the broken damage and dockage for all handling combinations studied in the pneumatic conveying system were obtained to be used in connection with pneumatic conveying for predicting broken damage in terms of relatively simpler dockage testing:

$$B = 12.85 + 2.88 \log_e D \qquad D < 4\%$$

$$B = -18.49 + 29.23 \log_e D \qquad D > 4\%$$

(4) The moisture content of corn affected the extent of the broken, small cracks, dockage, and devaluation number as well, resulting in higher amounts of each damage at lower moisture

level (12%).

(5) Size and/or shape of kernels was also a significant factor at least statistically, resulting in the order of significance, from the highest: round shape, large medium (flat), and small small (flat), the latter two of which were nearly the same. This order was coincident with the results of static compressive strength of kernels. Size and/or shape factor may be negligible in a practical application because of its little effect compared to that of air velocity and conveying length.

(6) Devaluation number--most interested in obtaining from this investigation--showed characteristic curves for different factors. Graphic differentiations for these curves indicated the rate of damage for different factors studied. The rate of damage with respect to conveying length was highest in the first stage of conveying and decreased rapidly with increased length for most of the air velocities studied.

(7) Based on the rate of damage versus air velocity curves, the upper limit of air velocity for conveying of low moisture corn (12%) may be proposed around 90 feet per second, in which range the damage rates were nearly the same regardless of conveying length. However, for higher moisture corn (20%), air velocity can be kept higher without causing extensive damage.

(8) The U.S. grading standard of corn should not be indicative of corn quality as far as total damage is concerned, because poor correlation between devaluation number and dockage

which has been used as a basis for one of the standard requirements in grading. However, if corn damage is limited only to the broken, the present basis for dockage may be a fairly good indication for grain damage, as explained by the relation given in Equation (9).

(9) The conventional range of conveying air velocity, such as recommended by Alden, may be too high to avoid the severe rate of total damage for low moisture corn.

RECOMMENDATIONS FOR ADDITIONAL WORK

The following suggestions are recommended for future work:

(1). Study the effect of several intermediate levels of corn moisture within the range used in this investigation on the extent of mechanical damage during pneumatic conveying.

(2). Study the mechanical damage of corn in a pneumatic conveyor by varying the number of elbows, size and length of conveying pipe, and feeding rate of grain.

(3). Study range of conveying air velocity applicable to any pneumatic conveying system based on the performance characteristics of the system as well as the extent of mechanical damage to corn.

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APPENDIX I

Mechnical Damage Data of Three Different Sizes and/or Shapes for Two Moisture Levels

Table 7. Mechanical damage of large medium flat yellow corn at 12 percent moisture content

Air velocity	Conveying length	Replication	Dockage	Broken	Large crack	Small crack	Total damage	Devaluation number
	Feet		Percent	Percent	Percent	Percent	Percent	Percent
V_o	0	Average 1/	0	7.48	3.35	12.42	23.26	0
(66 fps)	200	1	0.17	8.07	3.25	13.26	24.58	1.72
		2	0.15	5.50	9.24	11.10	25.84	3.38
	800	1	0.35	8.47	3.41	18.20	30.08	8.89
		2	0.40	10.73	6.58	15.06	32.37	11.87
	1600	1	0.55	10.33	2.92	22.84	36.09	16.73
		2	0.63	11.23	1.73	22.42	35.38	15.79
(86 fps)	200	1	0.33	7.87	4.98	18.90	31.75	11.06
		2	0.33	10.35	2.63	17.01	29.99	8.77
	800	1	0.81	11.21	2.39	20.31	33.91	13.88
		2	0.95	13.65	1.22	20.24	35.11	15.44
	1600	1	1.46	13.16	4.60	27.66	45.42	28.88
		2	1.66	13.24	1.18	25.45	39.87	21.54
(100 fps)	200	1	0.55	10.17	1.27	22.01	33.45	13.28
		2	0.63	10.83	1.51	34.31	46.65	30.48
	800	1	1.82	16.12	0.81	41.18	58.11	45.41
		2	2.09	17.45	0.72	46.08	64.25	53.41
	1600	1	3.80	26.55	1.71	47.01	75.27	67.77
		2	4.41	26.89	0.43	52.75	80.07	74.63

Table 7. (Cont'd)

Air velocity	Conveying length	Replication	Dockage	Broken	Large crack	Small crack	Totql damage	Devaluation Number
	Feet		Percent	Percent	Percent	Percent	Percent	Percent
(120 fps)	200	1	1.48	15.86	2.67	39.28	57.81	45.22
		2	1.40	14.00	1.87	33.11	48.98	33.52
	800	1	7.47	41.80	2.94	42.51	87.25	83.29
		2	6.44	42.16	0.87	41.12	84.15	79.35
	1600	1	21.69	76.50	1.49	19.21	97.20	96.35
		2	18.30	70.54	1.64	25.33	97.51	96.76

Table 8. Mechanical damage of large medium flat yellow corn at 20 percent moisture content

Air velocity	Conveying length	Replication	Dockage	Broken	Large crack	Small crack	Total damage	Devaluation number
	Feet		Percent	Percent	Percent	Percent	Percent	Percent
V_o	0	Average 1/	0	6.46	2.01	13.94	22.41	0
(66 fps)	200	1	0.05	7.49	1.85	15.88	25.22	3.62
		2	0.06	7.16	0.56	16.68	24.40	2.56
	800	1	0.13	5.77	2.21	19.83	27.81	6.96
		2	0.15	6.49	1.67	17.54	25.70	4.24
	1600	1	0.23	8.29	1.74	17.12	27.15	6.11
		2	0.25	7.96	1.50	16.85	26.31	5.03
(86 fps)	200	1	0.07	7.28	1.40	16.35	25.03	3.38
		2	0.10	8.71	1.16	14.48	24.35	2.50
	800	1	0.19	8.05	1.18	17.77	27.00	5.92
		2	0.27	7.67	0.19	15.56	23.42	1.30
	1600	1	0.36	7.75	0.59	19.51	27.85	7.01
		2	0.45	8.26	2.04	16.23	26.53	5.31
(100 fps)	200	1	0.10	9.76	0.61	15.59	25.96	4.57
		2	0.12	9.70	1.02	13.72	24.44	2.62
	800	1	0.33	9.77	1.11	14.13	25.01	3.35
		2	0.31	8.55	0.81	15.48	24.84	3.13
	1600	1	0.60	9.17	1.16	21.18	31.51	11.73
		2	0.58	7.47	1.79	23.48	32.74	13.31

Table 8. (Cont'd)

Air velocity	Conveying length	Replication	Dockage	Broken	Large crack	Small crack	Total damage	Devaluation Number
	Feet		Percent	Percent	Percent	Percent	Percent	Percent
(120 fps)	200	1	0.18	10.14	2.15	19.88	32.17	12.58
		2	0.19	7.33	1.28	17.78	26.39	5.13
	800	1	0.54	10.28	0.98	27.92	39.18	21.61
		2	0.53	8.42	0.28	20.74	29.44	9.06
	1600	1	1.13	12.06	0.66	32.39	45.11	29.26
		2	1.13	11.59	0.37	27.61	39.57	22.12

Table 9. Mechanical damage of round yellow corn at 12 percent moisture content

Air velocity	Conveying length	Replication	Dockage	Broken	Large crack	Small crack	Total damage	Devaluation number
	Feet		Percent	Percent	Percent	Percent	Percent	Percent
V_o	0	Average[1/]	0	6.92	3.25	14.47	24.65	0
(66 fps)	200	1	0.13	6.02	5.04	22.58	33.64	11.93
		2	0.13	6.02	5.38	14.96	27.66	3.99
	800	1	0.38	6.97	4.34	27.33	38.64	18.57
		2	0.40	8.61	4.96	16.20	29.77	6.79
	1600	1	0.67	8.03	5.69	25.46	39.18	19.28
		2	0.70	7.70	2.60	25.25	35.55	14.66
(86 fps)	200	1	0.30	6.57	6.62	26.32	39.51	19.71
		2	0.34	5.39	5.36	20.50	31.25	8.71
	800	1	1.15	8.80	3.60	27.62	40.02	20.40
		2	1.30	10.80	5.22	25.28	41.30	22.10
	1600	1	2.39	15.49	5.41	31.61	52.51	36.97
		2	2.70	15.40	4.07	31.70	51.17	35.19
(100 fps)	200	1	0.89	10.11	1.92	36.82	48.85	32.12
		2	0.79	7.90	2.39	36.46	46.75	29.33
	800	1	3.57	16.61	2.48	51.55	70.64	61.03
		2	3.22	17.34	2.02	47.89	67.25	56.53
	1600	1	7.49	27.50	1.48	55.00	83.98	78.74
		2	7.35	27.80	1.73	53.19	82.72	77.07

Table 9. (Cont'd)

Air velocity	Conveying length	Replication	Dockage	Broken	Large crack	Small crack	Total damage	Devaluation number
	Feet		Percent	Percent	Percent	Percent	Percent	Percent
(120 fps)	200	1	1.68	12.95	3.17	42.04	58.16	44.47
		2	1.96	14.17	2.53	42.36	59.06	45.67
	800	1	10.68	41.41	2.41	43.65	87.20	83.01
		2	10.28	37.80	3.80	46.84	88.44	84.66
	1600	1	26.46	71.57	2.78	23.64	97.99	97.33
		2	26.44	72.08	1.51	23.99	97.58	96.79

Table 10. Mechanical damage of round yellow corn at 20 percent moisture content

Air velocity	Conveying length	Replication	Dockage	Broken	Large crack	Small crack	Total damage	Devaluation number
	Feet		Percent	Percent	Percent	Percent	Percent	Percent
V_o	0	Average[1/]	0	4.55	2.65	14.34	21.53	0
(66 fps)	200	1	0.067	5.77	1.96	11.30	19.03	3.18
		2	0.045	5.18	2.48	18.28	25.94	5.62
	800	1	0.12	4.52	3.35	17.39	25.25	4.74
		2	0.13	6.08	0.95	21.87	28.90	9.39
	1600	1	0.15	6.10	2.69	17.83	26.62	6.49
		2	0.20	6.69	1.03	24.46	32.18	13.57
(86 fps)	200	1	0.09	6.25	2.03	17.96	26.24	6.00
		2	0.06	4.72	1.32	21.54	27.58	7.71
	800	1	0.21	6.00	1.57	21.92	29.49	10.14
		2	0.18	5.80	2.28	20.77	28.85	9.33
	1600	1	0.33	5.72	1.55	24.29	31.56	12.78
		2	0.32	7.08	1.65	27.87	36.60	19.20
(100 fps)	200	1	0.10	5.63	1.53	19.10	26.26	6.03
		2	0.08	4.52	2.77	23.40	30.69	11.67
	800	1	0.27	6.10	1.03	20.71	27.85	8.05
		2	0.22	6.13	2.57	20.91	29.61	10.30
	1600	1	0.53	8.85	0.94	25.65	35.44	17.73
		2	0.44	8.15	1.10	23.53	32.78	14.34

Table 10. (Cont'd)

Air velocity	Conveying length	Replication	Dockage	Broken	Large crack	Small crack	Total damage	Devaluation number
	Feet		Percent	Percent	Percent	Percent	Percent	Percent
(120 fps)	200	1	0.13	5.86	1.50	23.24	30.60	11.56
		2	0.13	5.22	2.16	25.49	32.87	14.45
	800	1	0.50	6.58	0.83	26.82	34.23	16.18
		2	0.48	8.37	0.53	26.14	35.04	17.22
	1600	1	1.16	11.28	0.98	28.72	40.98	24.79
		2	1.24	7.57	1.49	33.45	42.51	26.74

Table 11. Mechanical damage of small small flat yellow corn at 12 percent moisture content

Air velocity	Conveying length	Replication	Dockage	Broken	Large crack	Small crack	Total damage	Devaluation number
	Feet		Percent	Percent	Percent	Percent	Percent	Percent
V_o	0	Average[1/]	0	10.15	2.16	10.99	23.30	0
(66 fps)	200	1	0.21	7.83	2.00	15.36	25.18	2.50
		2	0.23	10.90	0.86	13.55	25.31	2.67
	800	1	0.43	10.68	3.18	10.31	24.17	1.19
		2	0.61	12.48	1.05	15.34	28.87	7.31
	1600	1	0.65	11.83	2.95	16.15	30.93	10.00
		2	1.01	13.12	1.04	16.24	30.40	9.29
(86 fps)	200	1	0.54	13.00	2.08	10.51	25.59	3.03
		2	0.56	11.48	0.98	12.69	25.15	2.46
	800	1	1.41	13.24	1.53	15.44	30.21	9.06
		2	1.56	12.16	1.03	20.46	33.65	13.54
	1600	1	2.33	15.41	1.43	25.07	41.91	24.30
		2	2.66	17.65	1.79	31.51	50.95	26.08
(100 fps)	200	1	1.09	12.84	0.54	18.40	31.78	11.10
		2	0.87	13.54	0.52	20.46	34.52	14.67
	800	1	3.17	18.07	1.64	33.53	53.24	39.07
		2	2.63	18.76	1.32	34.87	54.95	41.30
	1600	1	6.19	29.89	1.43	41.88	73.20	65.08
		2	4.99	24.63	1.60	43.30	69.53	60.29

Table 11. (Cont'd)

Air velocity	Conveying length	Replication	Dockage	Broken	Large crack	Small crack	Total damage	Devaluation number
	Feet		Percent	Percent	Percent	Percent	Percent	Percent
(120 fps)	200	1	1.87	16.86	1.37	30.49	48.72	33.18
		2	1.91	18.56	0.72	28.11	47.39	31.44
	800	1	9.08	40.42	2.92	37.58	80.92	75.14
		2	8.30	36.80	1.94	42.49	81.23	75.54
	1600	1	23.22	72.96	1.05	20.18	94.19	92.43
		2	20.85	70.67	1.16	24.53	96.36	95.26

Table 12. Mechanical damage of small small flat yellow corn at 20 percent moisture content

Air velocity	Conveying length	Replication	Dockage	Broken	Large crack	Small crack	Total damage	Devaluation number
	Feet		Percent	Percent	Percent	Percent	Percent	Percent
V_o	0	Average[1]	0	13.28	0.59	14.85	28.71	0
(66 fps)	200	1	0.151	12.80	1.04	16.13	30.01	1.82
		2	0.206	14.86	0.37	16.53	31.76	4.28
	800	1	0.393	12.32	0.93	18.54	31.78	4.31
		2	0.477	13.80	1.22	17.68	32.75	5.67
	1600	1	0.703	15.48	1.02	18.02	34.52	8.15
		2	0.758	15.04	1.16	20.12	36.31	10.66
(86 fps)	200	1	0.321	12.77	0.71	17.72	31.20	3.49
		2	0.291	13.87	0.52	16.88	31.27	3.59
	800	1	0.791	17.34	0.83	15.88	34.06	7.50
		2	0.834	16.00	1.34	16.45	34.21	7.71
	1600	1	1.23	16.16	0.58	19.49	36.83	11.39
		2	1.30	16.18	0.41	17.85	35.08	8.94
(100 fps)	200	1	0.334	11.94	0.93	17.30	30.19	2.08
		2	0.375	15.79	0.91	16.26	32.20	3.49
	800	1	0.931	14.20	0.65	16.30	31.29	3.62
		2	1.115	15.34	0.80	19.67	35.80	9.95
	1600	1	1.53	15.46	0.90	22.06	38.41	13.61
		2	1.84	12.81	1.09	24.84	38.34	13.65

Table 12. (Cont'd)

Air velocity	Conveying length	Replication	Dockage	Broken	Large crack	Small crack	Total damage	Devaluation number
	Feet		Percent	Percent	Percent	Percent	Percent	Percent
(120 fps)	200	1	0.648	14.85	0.96	19.33	35.13	9.01
		2	0.707	14.25	0.85	20.55	35.66	9.75
	800	1	1.81	15.89	0.92	26.86	43.67	20.99
		2	1.97	14.84	0.74	24.46	40.04	15.89
	1600	1	3.28	18.84	0.76	28.70	48.29	27.48
		2	3.63	18.34	0.92	25.24	44.51	22.16

APPENDIX II

Analysis of Variance of Small Cracks,
Broken Damage, Dockage, and Devaluation Number
for Two Moisture Levels

Table 13. Analysis of variance, 12% moisture, (small crack)

Source of variation	df	SS	MS	F
Replication	1	1.76	1.76	.173
Treatment	35	9827.04	280.77	27.66 **
S	2	1009.44	504.72	49.73 **
V	3	5434.47	1811.49	178.47 ***
L	2	674.80	337.40	33.24 **
S x V	6	145.66	24.28	2.39
S x L	4	56.78	14.20	1.399
V x L	6	2386.07	397.68	39.18 **
S x V x L	12	119.82	9.98	.98
Error	35	355.33	10.15	
Total	71	10184.13		

* Significant at $\alpha = 0.05$
** Significant st $\alpha = 0.01$
*** Very highly significant

Table 14. Analysis of variance, 20% moisture, (small crack)

Source of variation	df	SS	MS	F
Replication	1	1.86	1.86	.41
Treatment	35	1319.57	37.70	8.38 *
S	2	182.59	91.30	20.29 **
V	3	600.67	200.22	44.49 **
L	2	330.55	165.28	36.73 **
S x V	6	50.14	8.36	1.86
S x L	4	4.25	1.06	.24
V x L	6	88.36	14.73	3.27 *
S x V x L	12	63.01	5.25	1.17
Error	35	174.92	4.50	
Total	71	1496.35		

* Significant at $\alpha = 0.05$
** Significant at $\alpha = 0.01$
*** Very highly significant

Table 15. Analysis of variance based on the broken data with 12% moisture content

Source of variation	df	SS	MS	F
Replication	1	0.11	0.11	0.046
Treatment	35	23430.89	669.45	280.69 ***
S	2	76.85	38.43	16.13 **
V	3	12519.55	4173.18	1749.76 ***
L	2	5097.73	2548.86	1068.70 ***
S x V	6	26.64	4.44	1.862
S x L	4	28.54	7.14	2.994
V x L	6	5648.48	941.41	394.72 ***
S x V x L	12	33.10	2.76	1.157
Error	35	83.49	2.385	
Total	71	23514.49		

* Significant at $\alpha = 0.05$
** Significant at $\alpha = 0.01$
*** Very highly significant

Table 16. Analysis of variance based on the broken data for 20% moisture corn

Source of variation	df	SS	MS	F
Replication	1	0.61	0.61	.54
Treatment	35	1089.21	21.12	27.61 **
S	2	949.63	474.82	421.31 ***
V	3	45.73	15.24	13.52 **
L	2	35.83	17.92	15.90 **
S x V	6	10.24	1.71	1.52
S x L	4	7.9	1.975	1.75
V x L	6	23.97	3.995	3.54 *
S x L x V	12	15.91	1.326	1.18
Error	35	39.46	1.127	
Total	71	1129.28		

* Significant at $\alpha = 0.05$
** Significant at $\alpha = 0.01$
*** Very highly significant

Table 17. Analysis of variance for dockage data (12% moisture content)

Source of variation	df	SS	MS	F
Replication	1	0.096	0.096	0.348
Treatment	35	3740.50	107.15	388.23 ***
S	2	35.66	17.83	64.60 **
V	3	2034.44	678.15	2457.06 ***
L	2	1021.32	510.66	1850.21 ***
S x V	6	18.6	3.10	11.23 *
S x L	4	12.21	3.05	11.05 *
V x L	6	614.11	102.35	370.83 ***
S x V x L	12	13.92	1.16	4.20 *
Error	35	9.66	.276	
Total	71	3750.26		

* Significant at $\alpha = 0.05$
** Significant at $\alpha = 0.01$
*** Very highly significant

Table 18. Analysis of variance for dockage data (20% moisture)

Source of variation	df	SS	MS	F
Replication	1	0.22	0.22	3.97
Treatment	35	309.77	8.85	159.66 ***
S	2	104.21	52.11	940.12 ***
V	3	75.83	25.28	456.08 ***
L	2	99.81	49.81	898.63 ***
S x V	6	7.61	1.278	22.87 **
S x L	4	7.12	1.780	32.11 **
V x L	6	14.75	2.458	44.34 **
S x V x L	12	.41	0.034	.613
Error	35	1.94	0.03771	
Total	71	311.29		

* Significant at $\alpha = 0.05$
** Significant at $\alpha = 0.01$
*** Very highly significant

Table 19. Analysis of variance for devaluation number (12 percent moisture content)

Source of variation	df	SS	MS	F
Replication	1	3.53	3.53	.219
Treatment	35	64744.57	1849.84	114.98 ***
S	2	1398.93	699.465	43.48 **
V	3	43954.0	14651.33	910.66 ***
L	2	13924.16	6962.08	432.73 ***
S x V	6	208.79	34.80	2.16
S x L	4	17.90	4.475	.278
V x L	6	5143.31	857.22	53.28 **
S x V x L	12	97.48	8.123	.505
Error	35	563.1	16.089	
Total	71	65311.2		

* Significant at $\alpha = 0.05$
** Significant at $\alpha = 0.01$
*** Very highly significant

Table 20. Analysis of variance for devaluation number (20 percent moisture content)

Source of variation	df	SS	MS	F
Replication	1	0.06	0.06	.0069
Treatment	35	2950.15	84.29	9.74 **
S	2	190.45	95.23	11.01 **
V	3	1488.35	496.12	57.35 ***
L	2	950.07	475.04	54.92 ***
S x V	6	47.48	7.91	.91
S x L	4	17.46	4.37	.51
V x L	6	204.24	34.04	3.94 *
S x V x L	12	52.10	4.34	.50
Error	35	302.62	8.65	
Total	71	3252.83		

* Significant at $\alpha = 0.05$
** Significant at $\alpha = 0.01$
*** Very highly significant

APPENDIX III

Graphical Presentation of Mechanical Damage

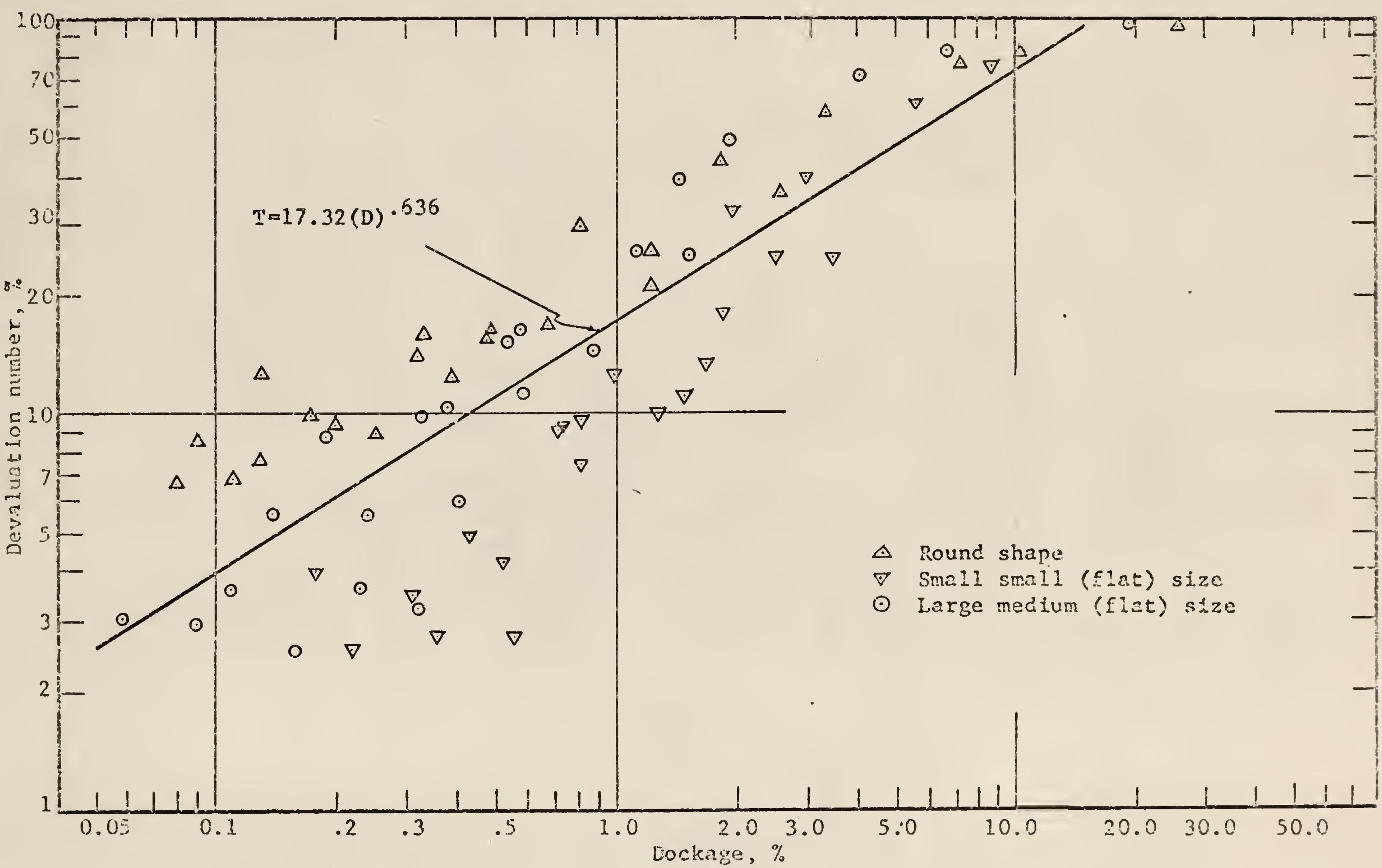


Fig. 1 Plot of devaluation number of total damage versus dockage.

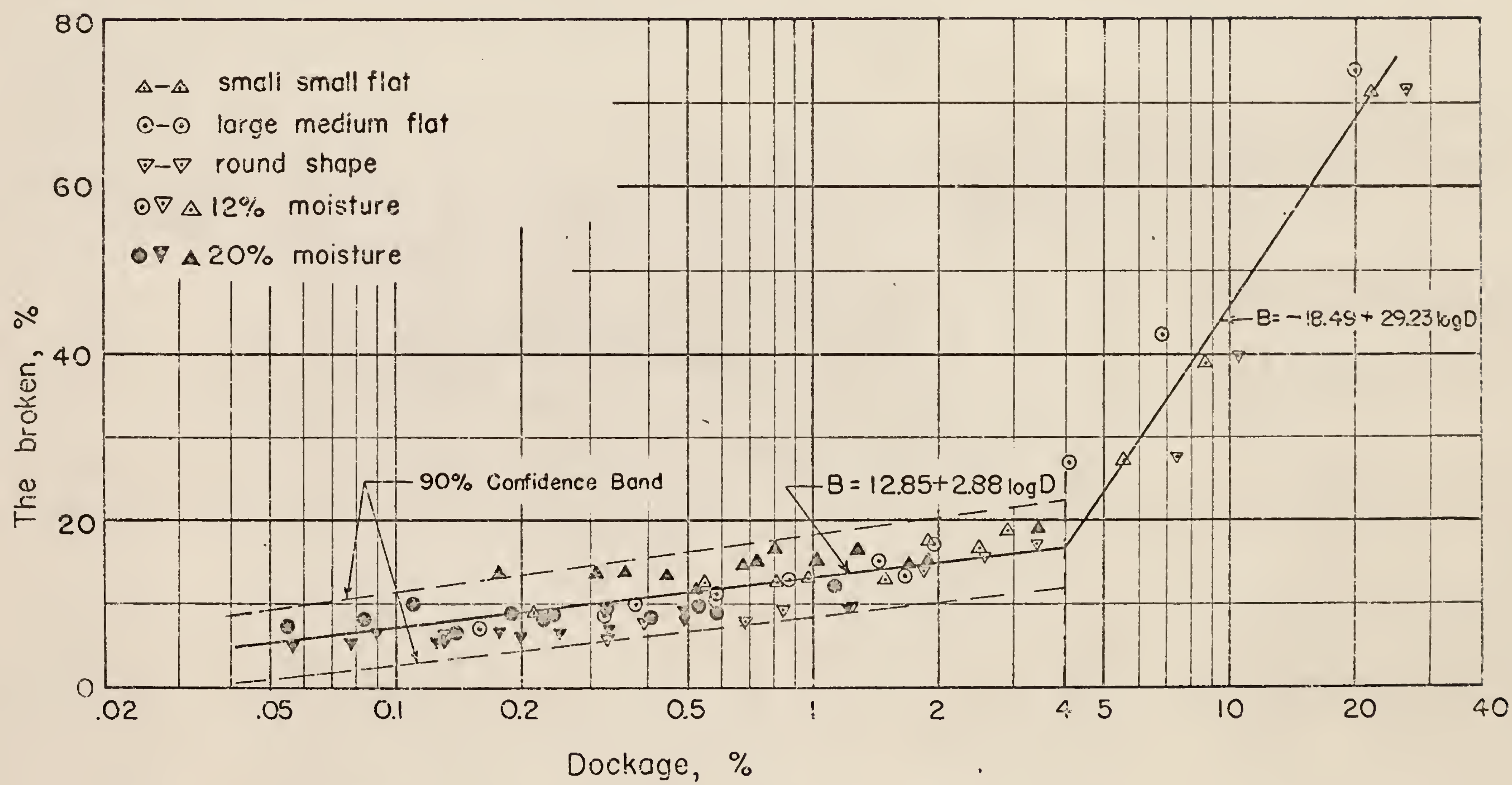


Fig. 2 Relation between the broken and dockage for every combination of treatment.

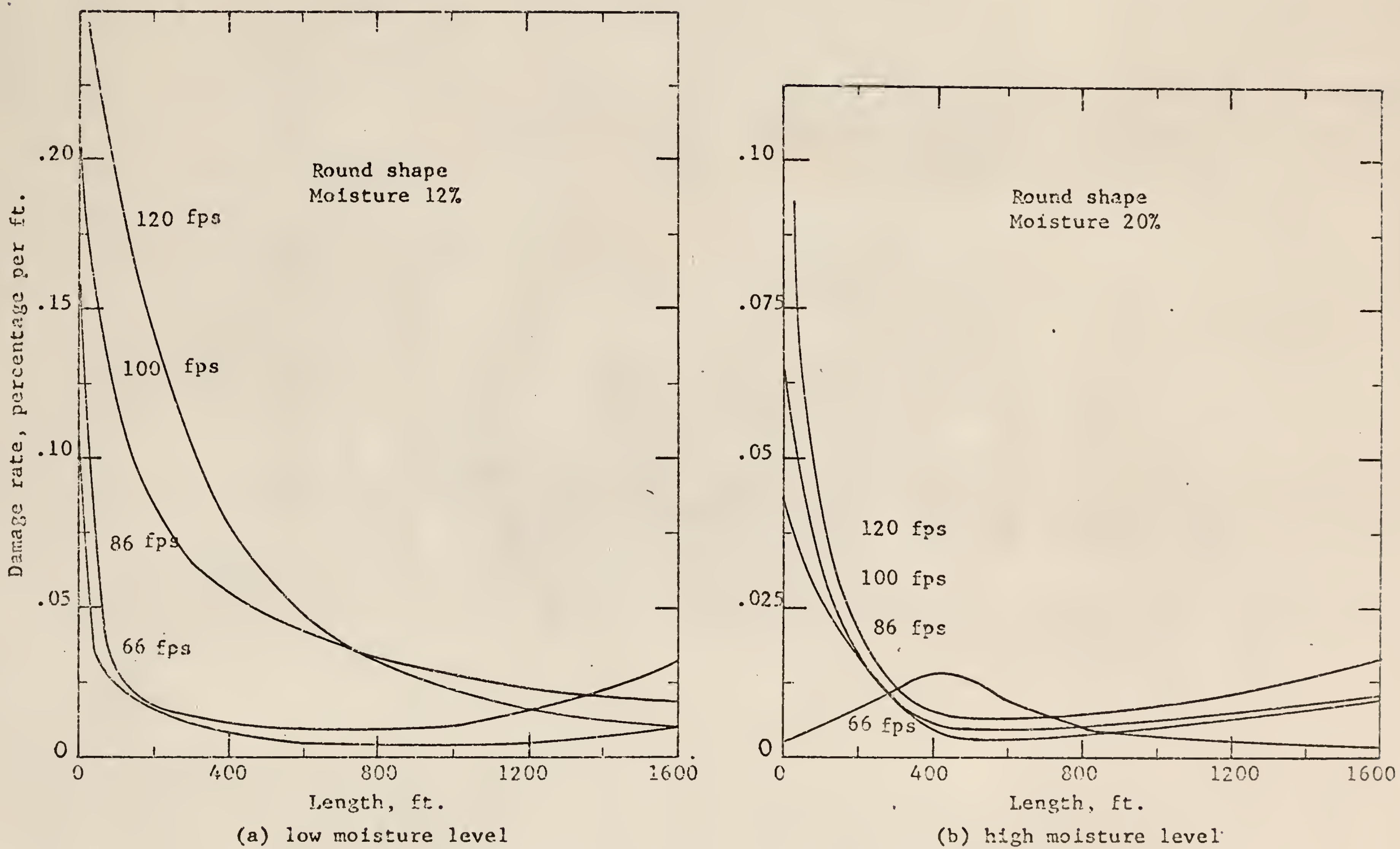


Fig. 3 Damage rate relative to conveying length versus conveying length for four air velocities.

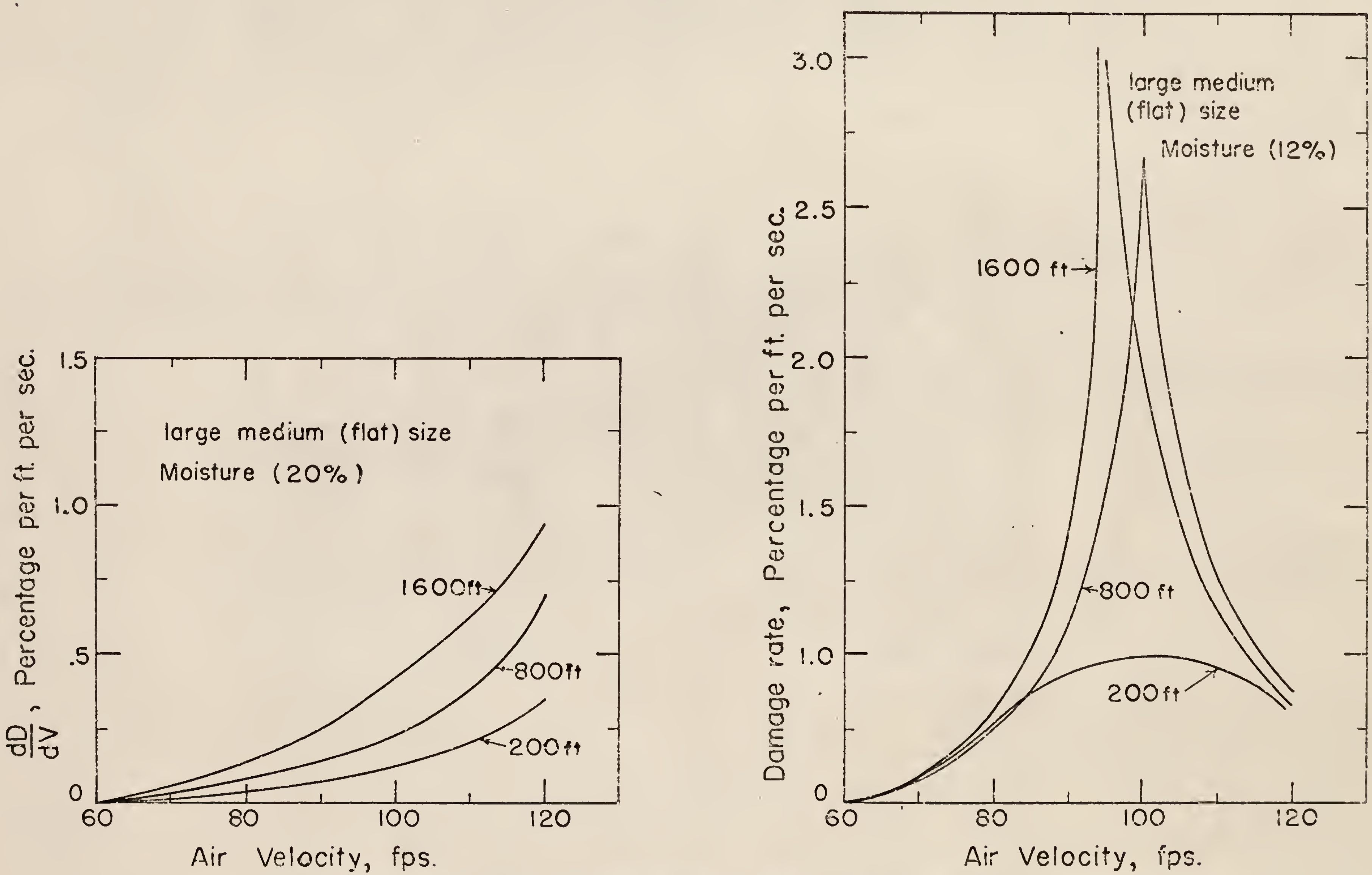
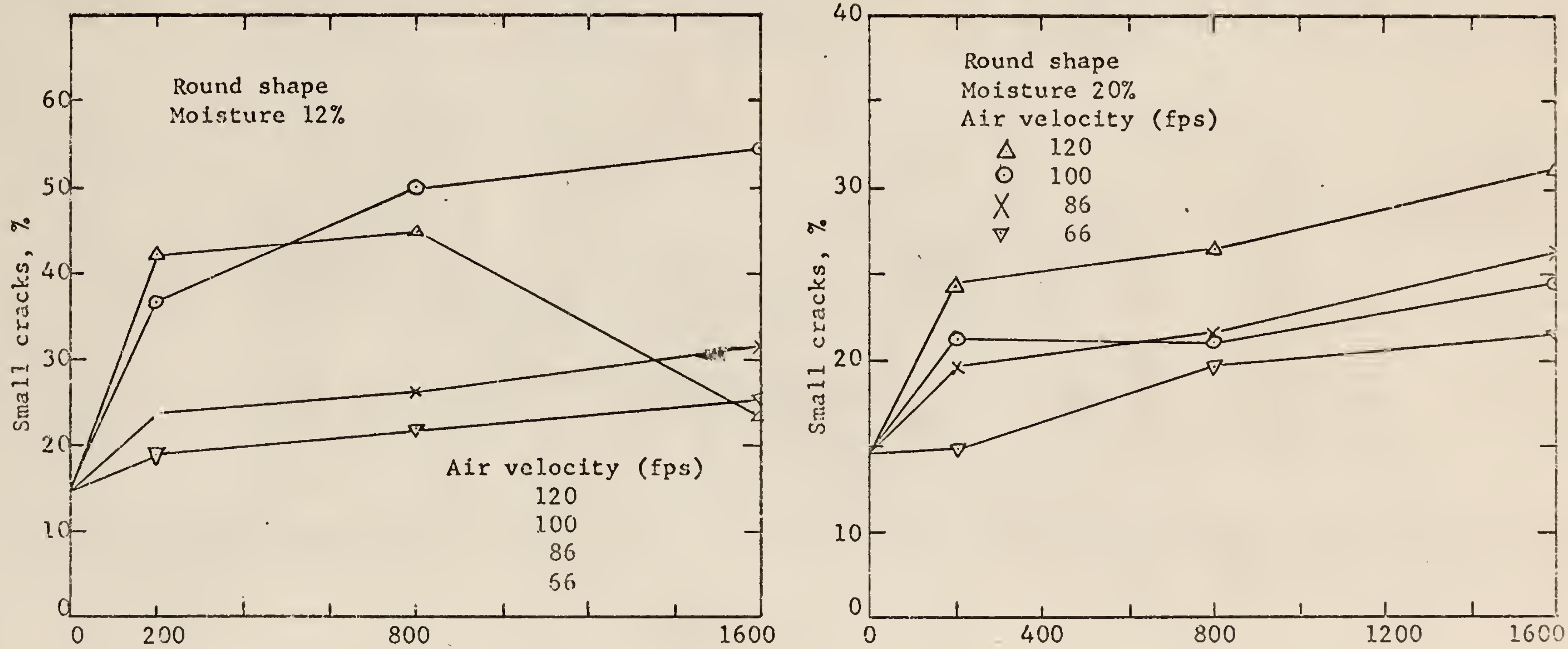


Fig. 4 Plot of relationship between damage rate with respect to air velocity. and air velocity.



(a) low moisture level
Conveying length, ft.

(b) high moisture level

Fig. 5 Small cracks to round shape corn at different air velocities.

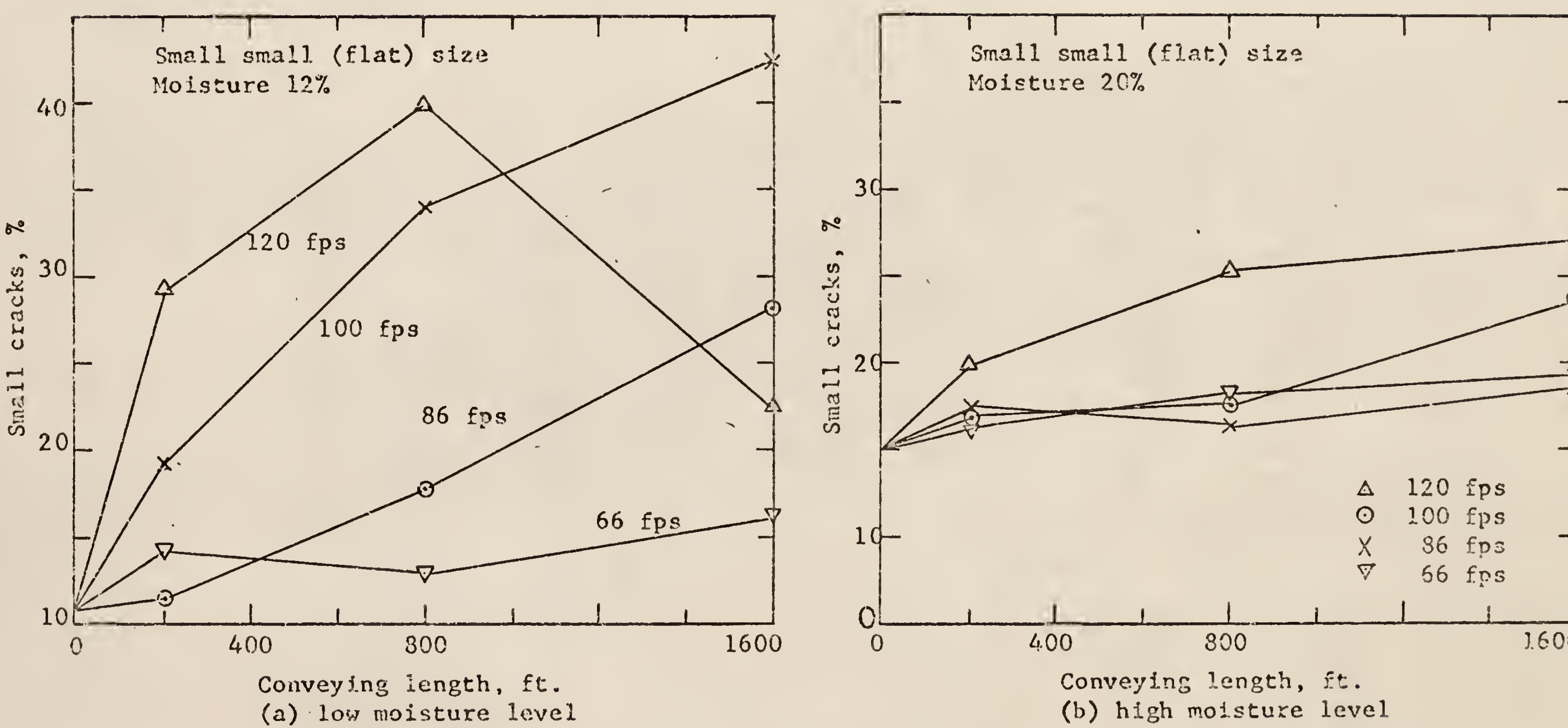


Fig. 6 Small cracks to small small (flat) size corn at different air velocities.

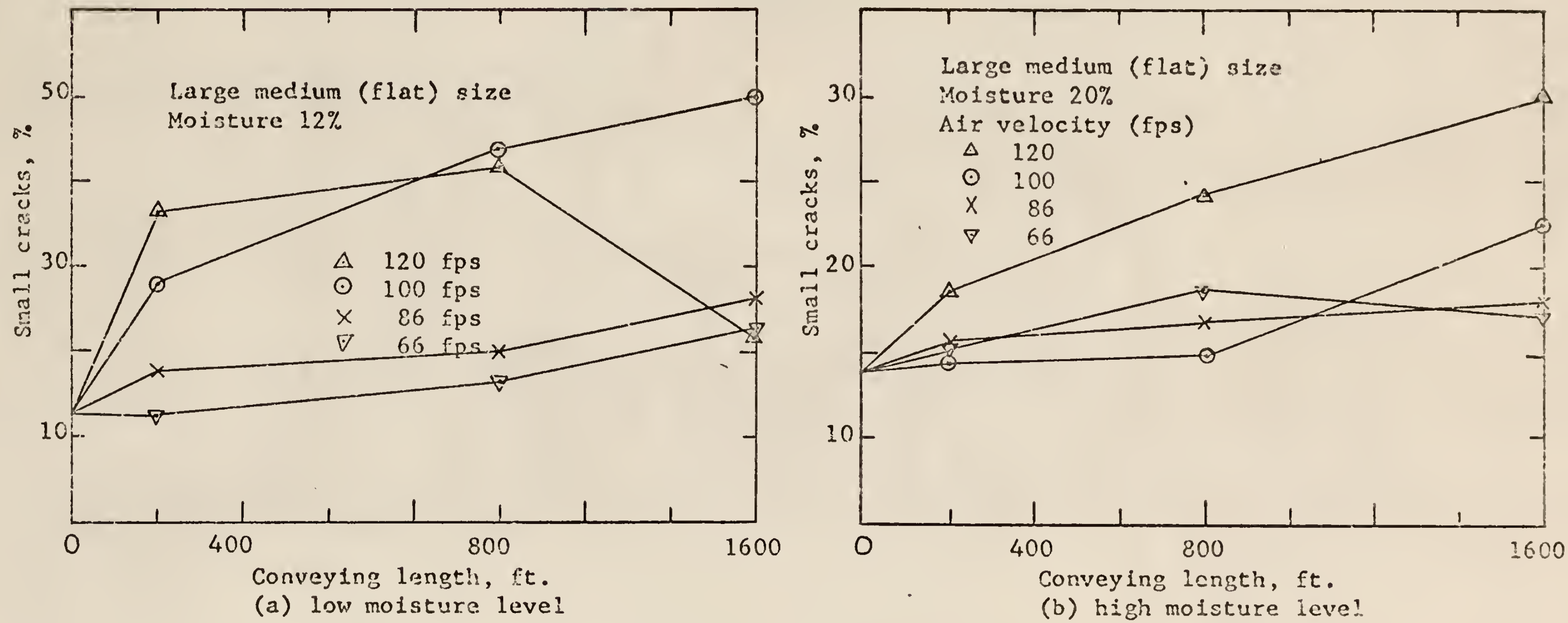


Fig. 7 Small cracks to large medium (flat) size corn at different air velocities.

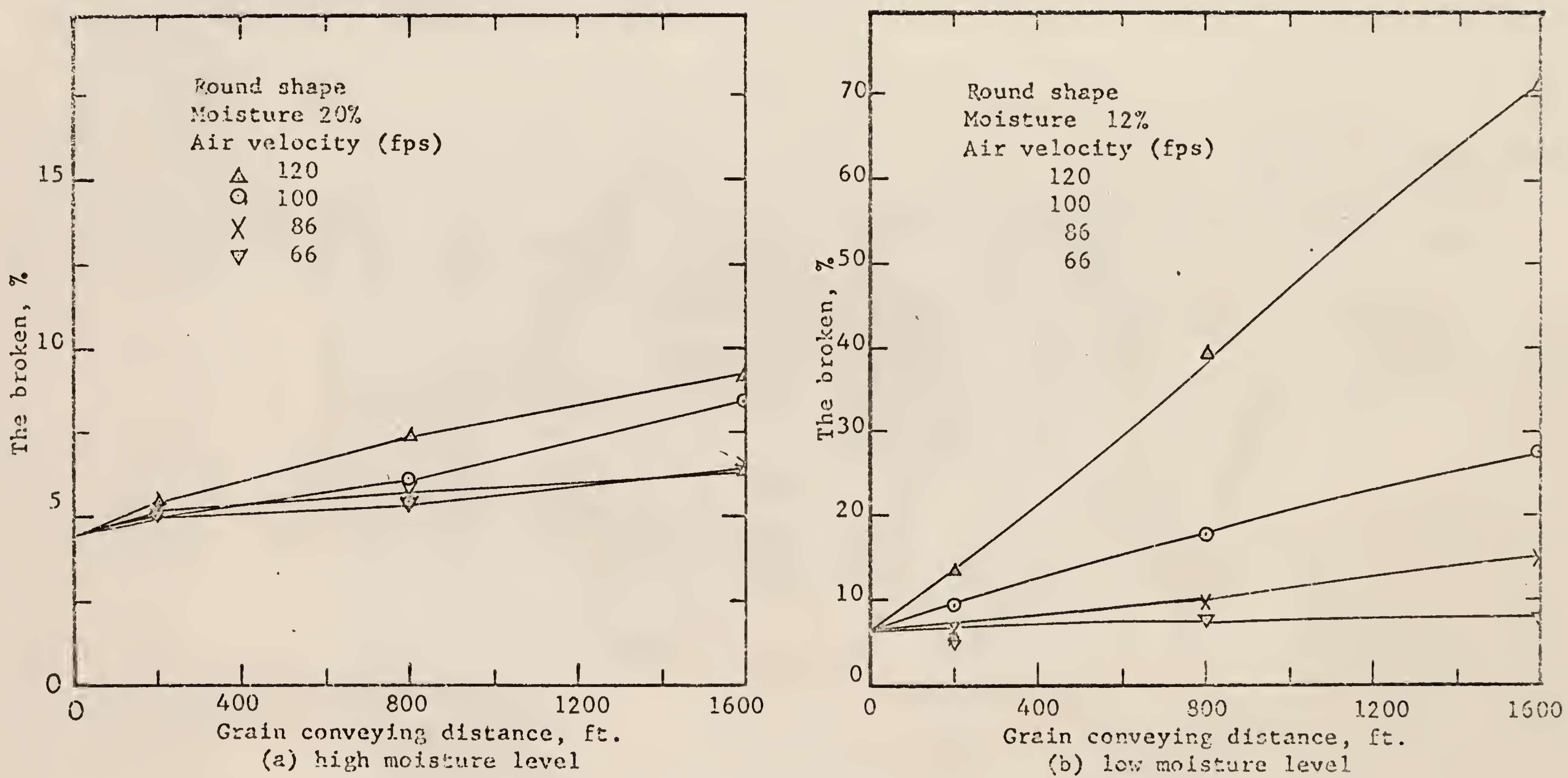


Fig. 8 The broken damage to round-shaped corn at different conveying air velocities.

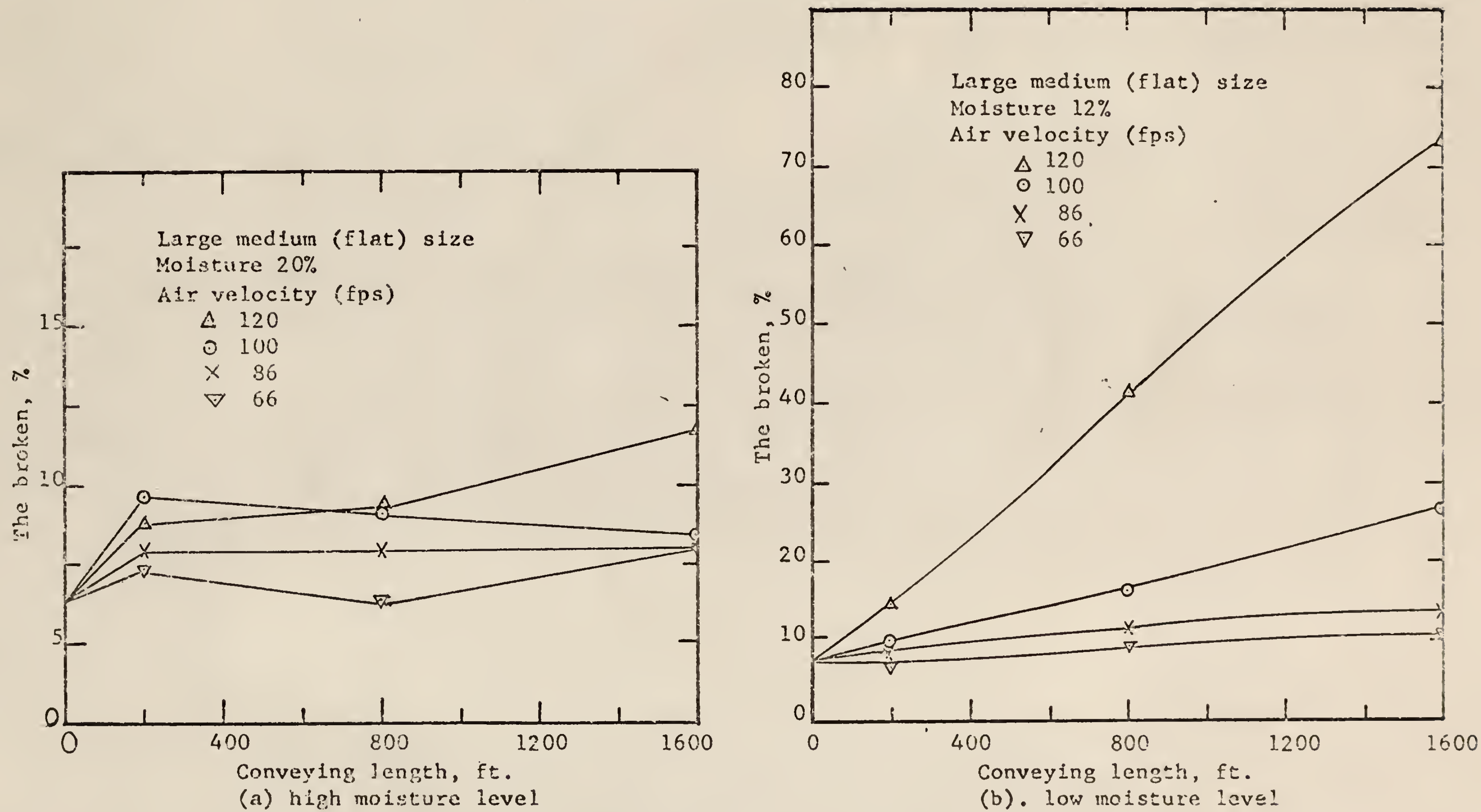


Fig. 9 The broken damage to large medium size corn at different air velocities.

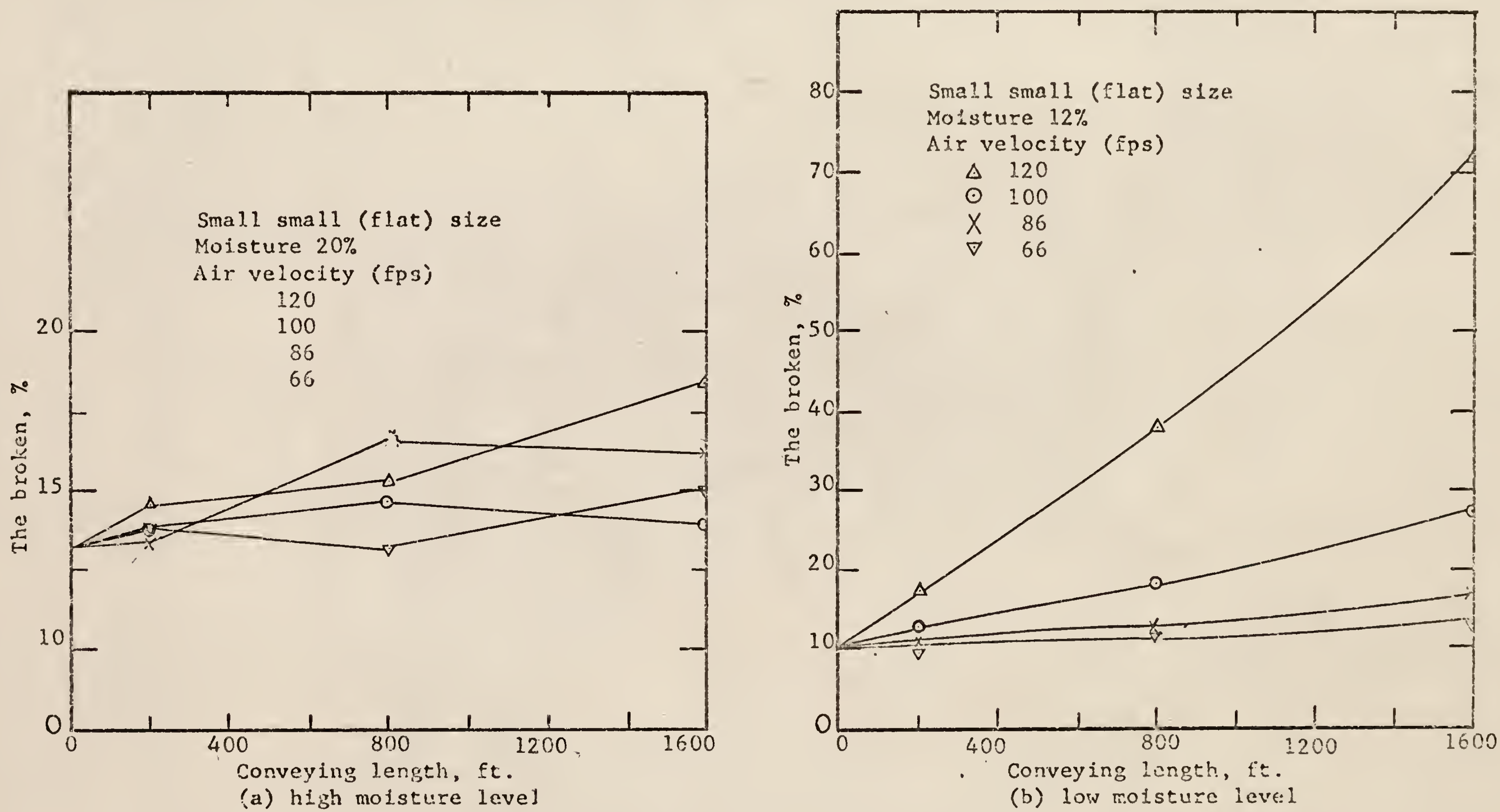


Fig. 10 The broken damage to small small (flat) size corn at different air velocities.

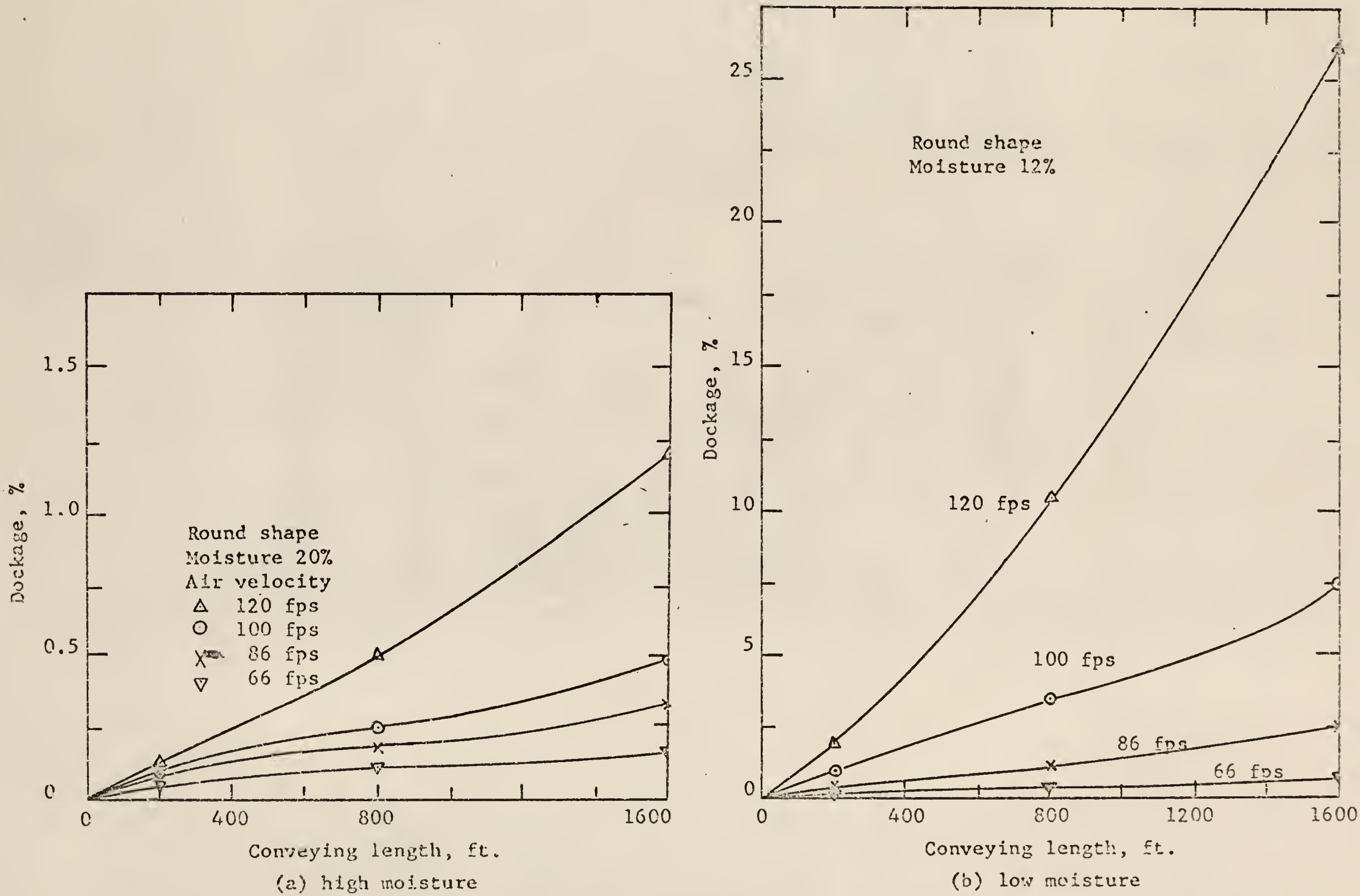
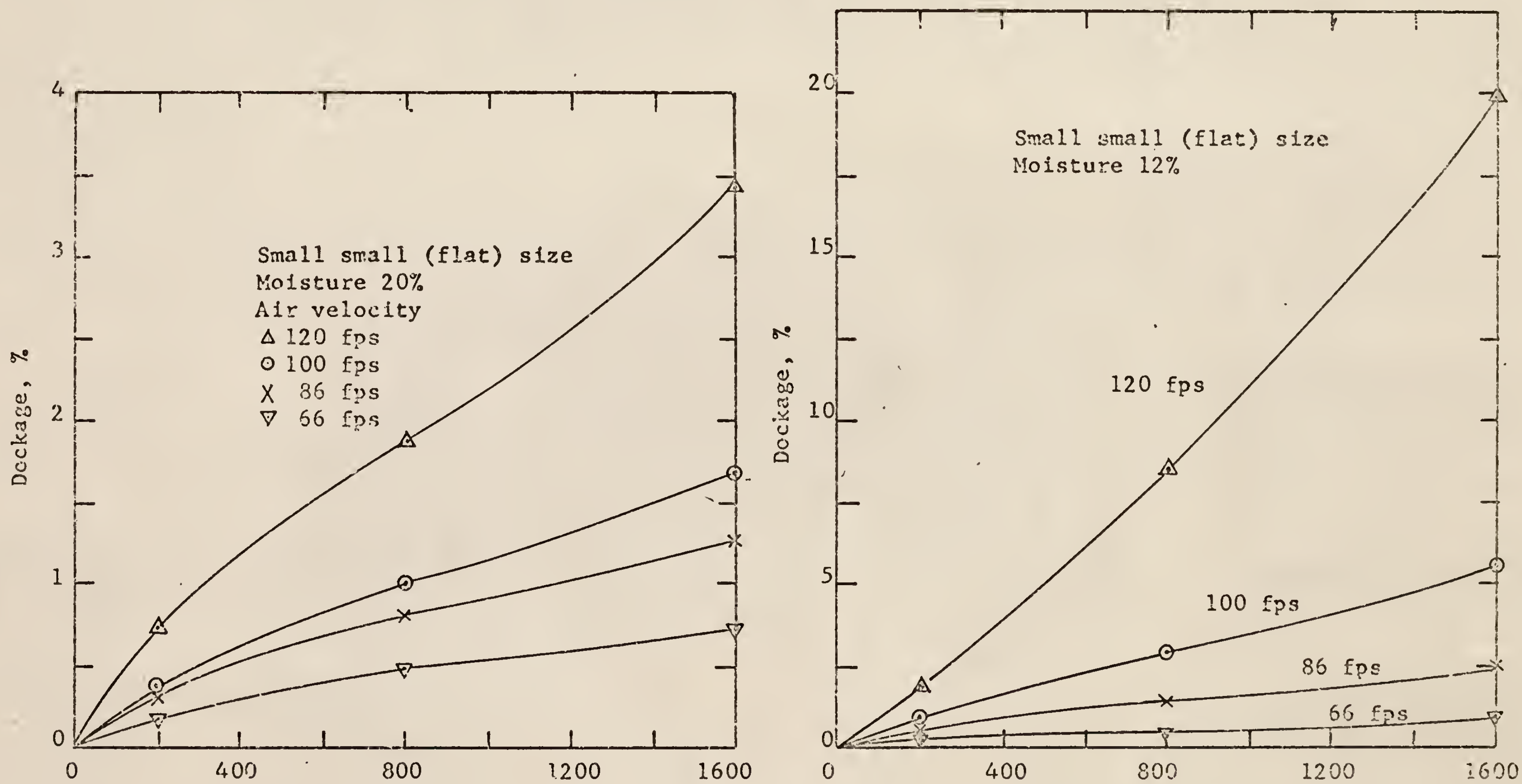


Fig. 11. Dockage of round shape corn versus conveying length for different air velocities.



(a) high moisture level

(b) low moisture level

Fig. 12 Dockage of small small (flat) size corn versus conveying lengths for four different air velocities.

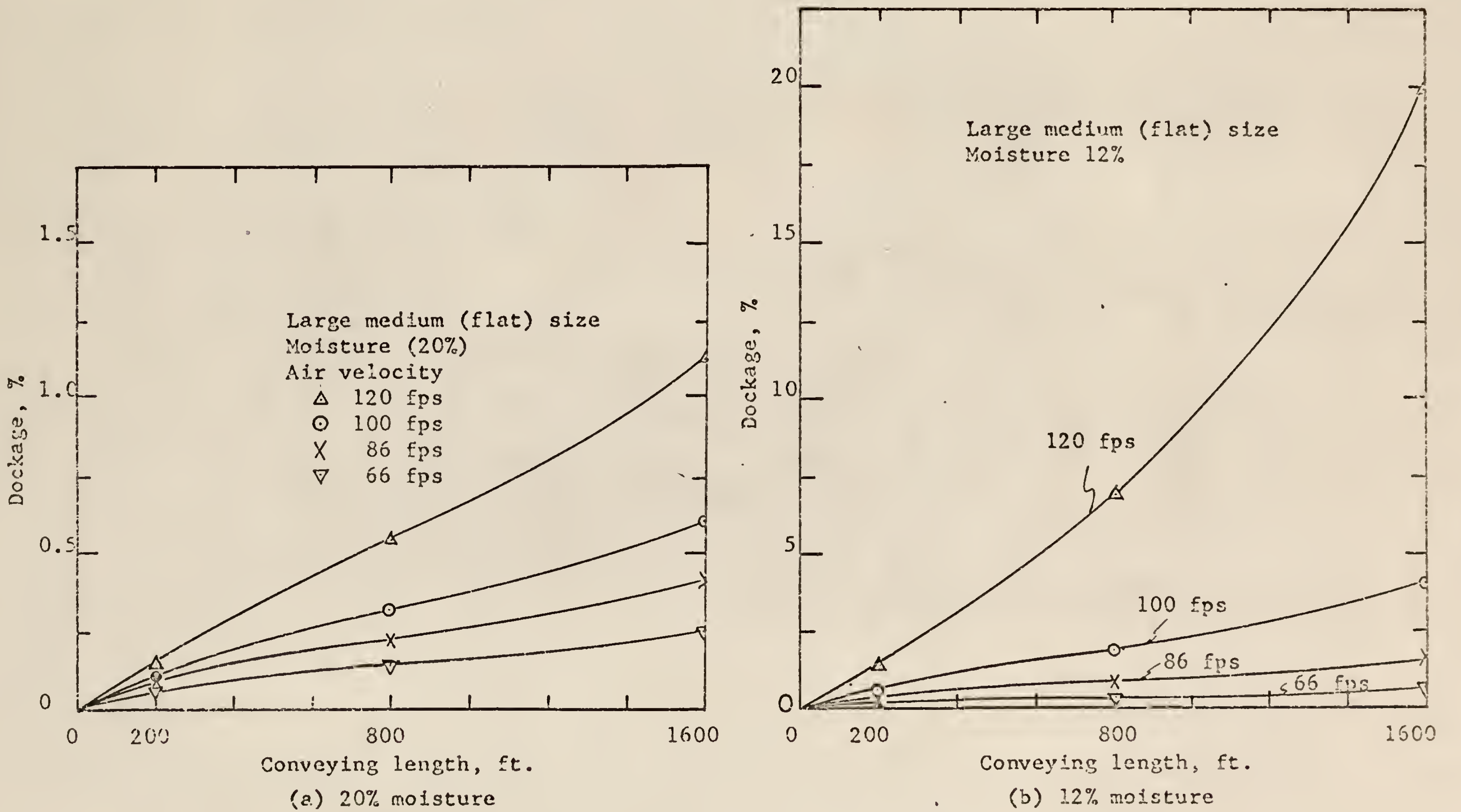


Fig. 13 Dockage of large medium (flat) size corn versus conveying length for four different air velocities.

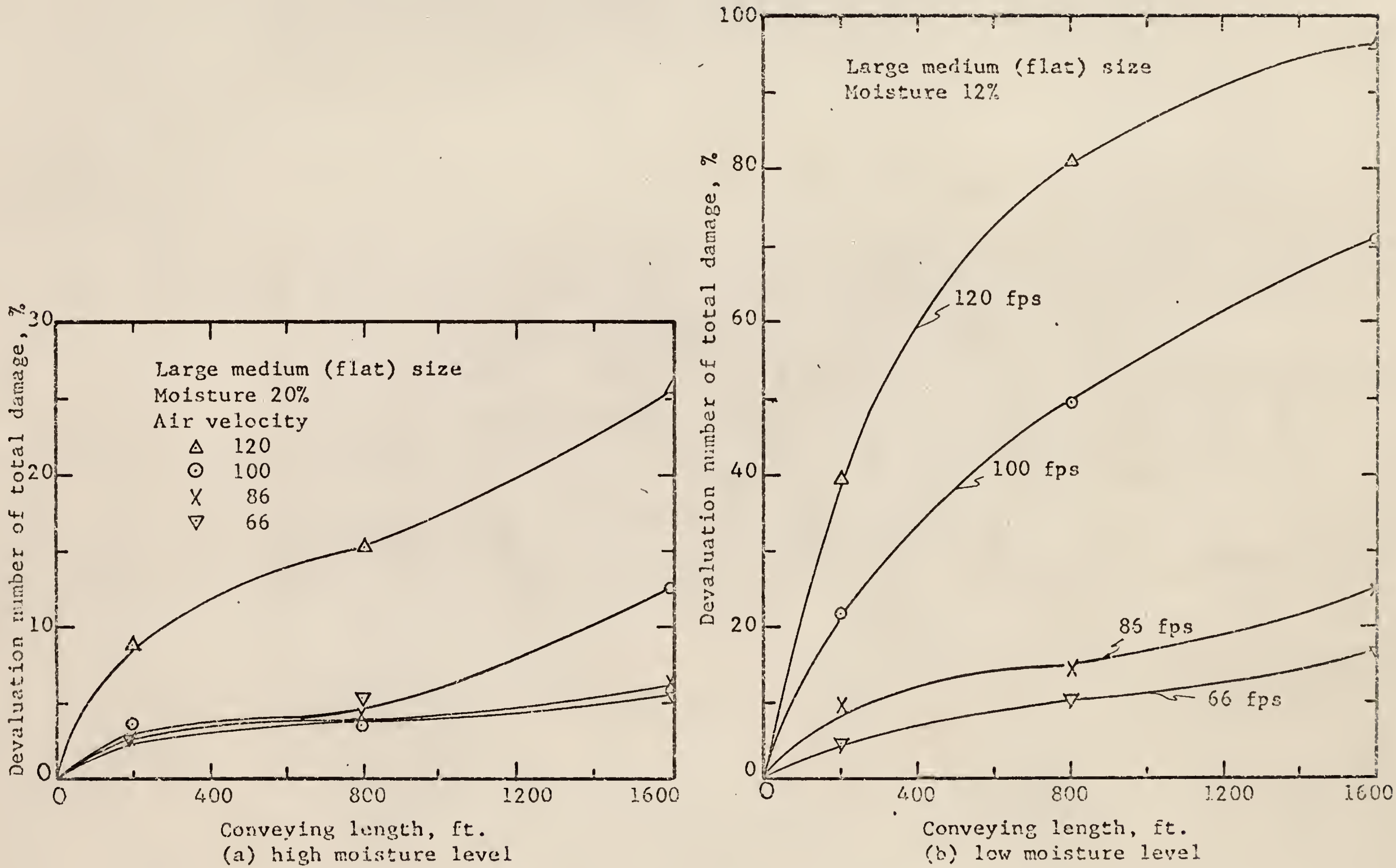


Fig. 14 Devaluation number of total damage to large medium (flat) corn versus conveying length for four different air velocities.

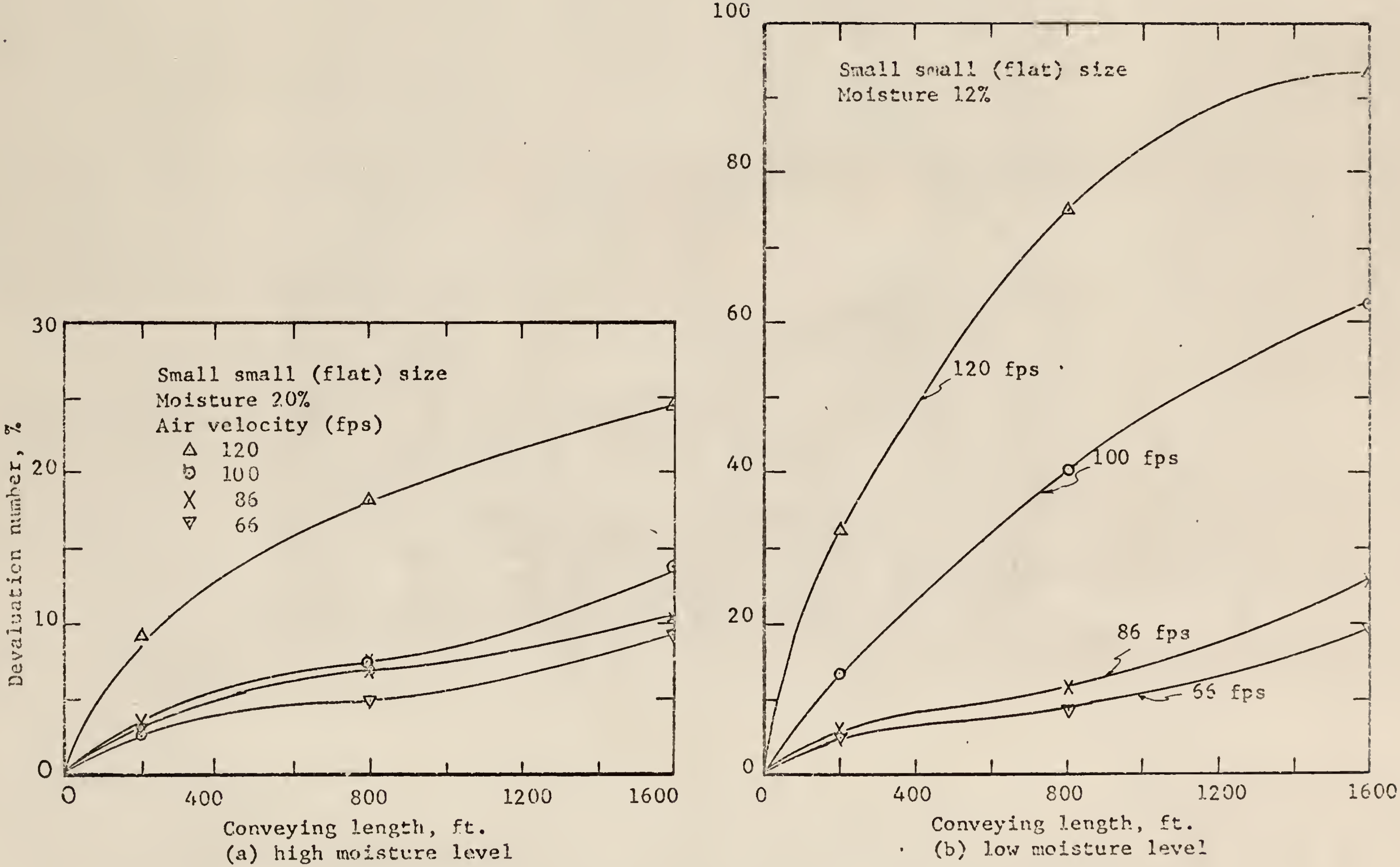


Fig. 15 Devaluation number of total damage for small small (flat) size corn versus conveying length for four different air velocities.

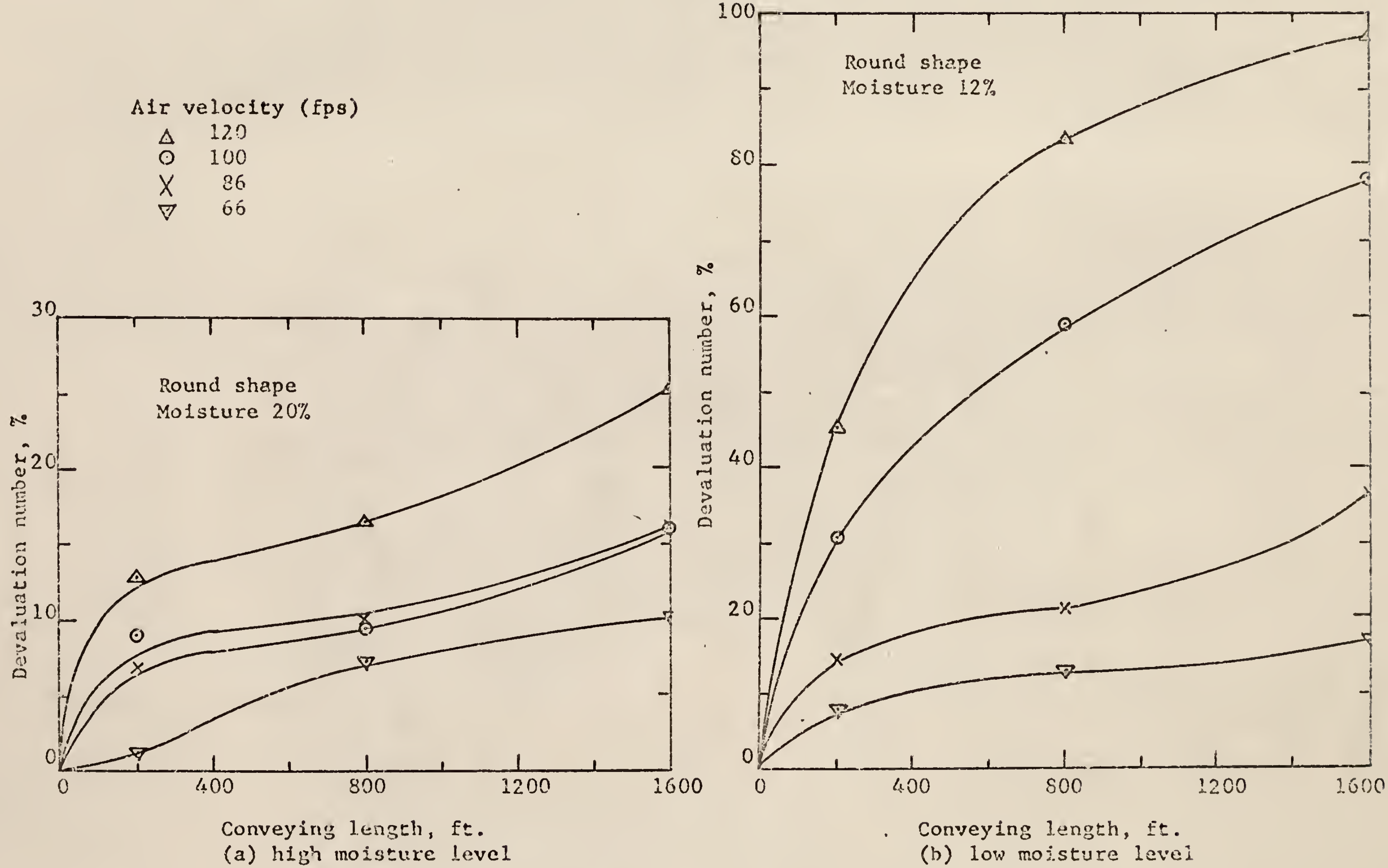


Fig. 16 Devaluation number of total damage to round shape corn versus conveying length for four different air velocities.

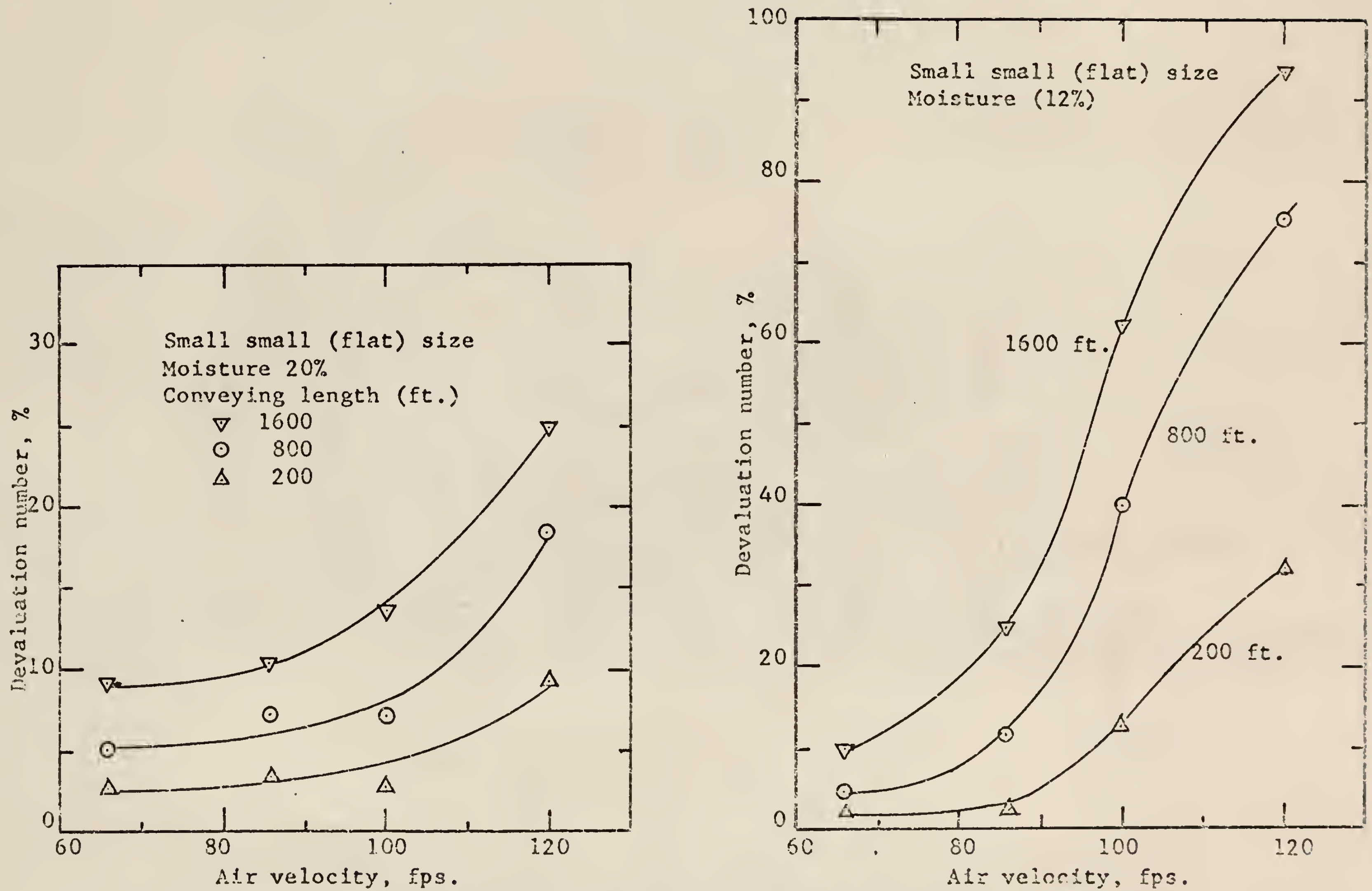


Fig. 17 Devaluation number of total damage to small small (flat) corn versus conveying air velocity for three different conveying lengths.

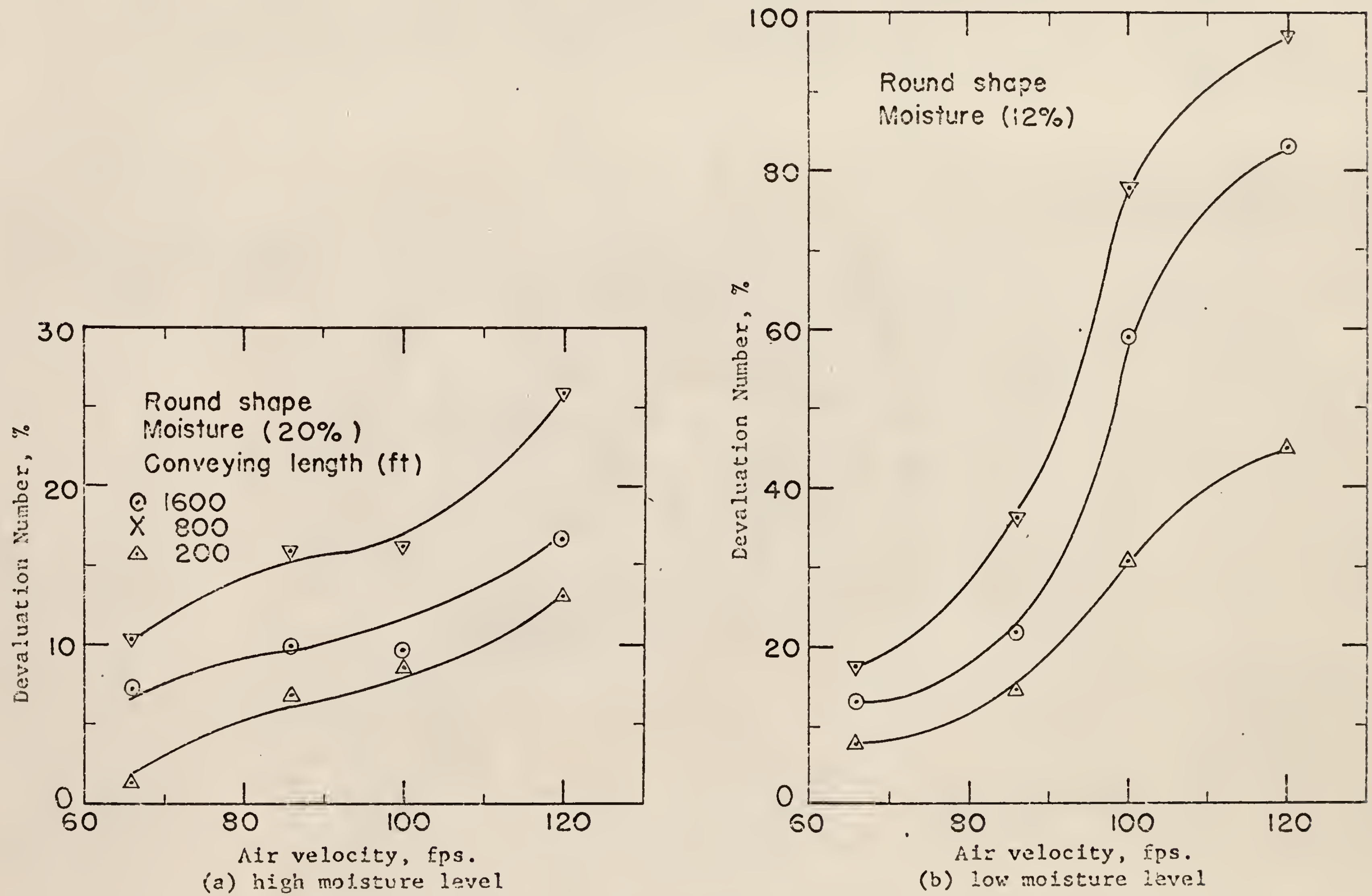


Fig. 18 Devaluation number of total damage for round shape corn versus air velocity for three different conveying lengths.

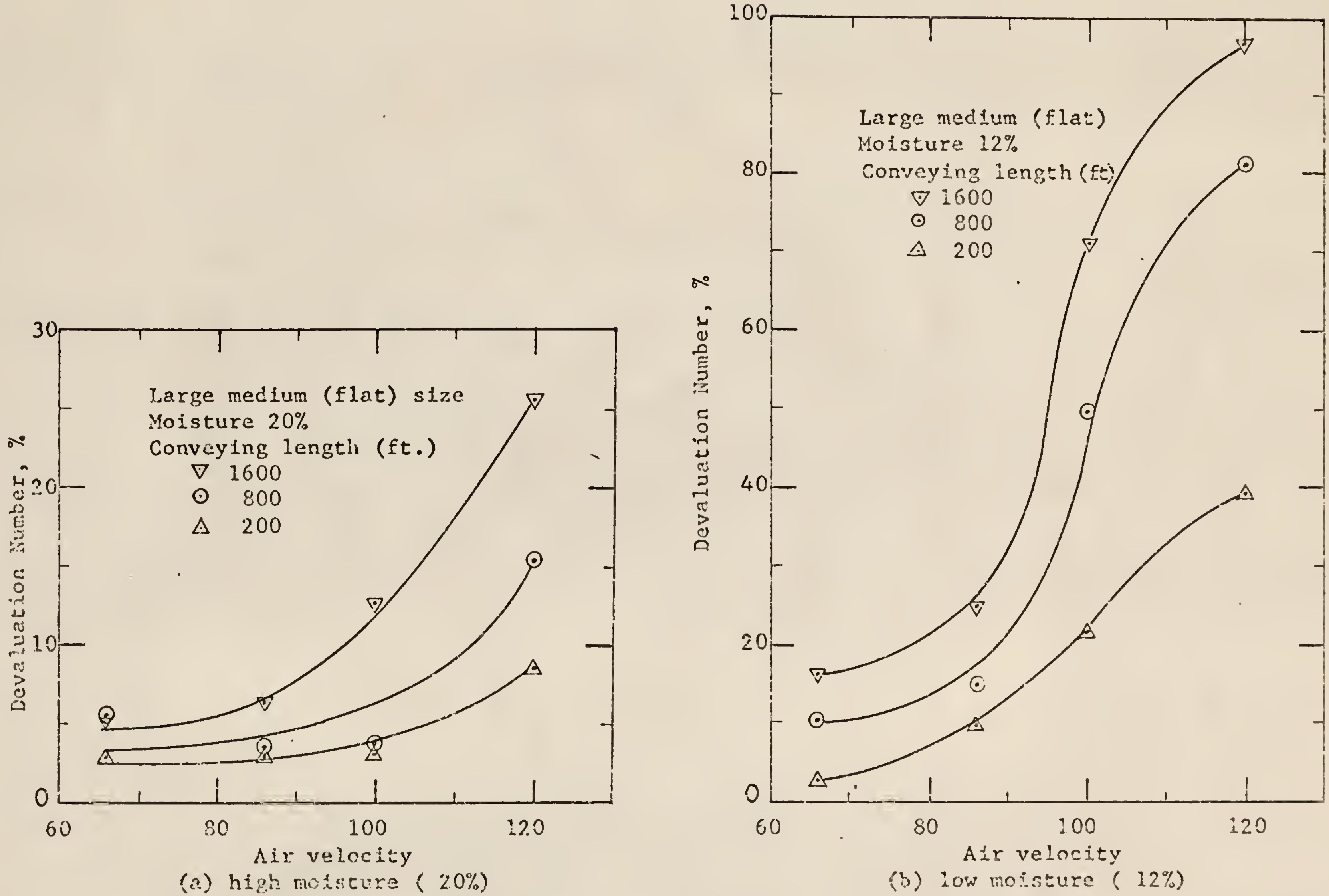


Fig. 19 Devaluation number of total damage to large medium (flat) size corn versus conveying air velocity for three conveying lengths.

MECHANICAL DAMAGE TO CORN IN A PNEUMATIC CONVEYING SYSTEM

by

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AN ABSTRACT OF A MASTER'S THESIS

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ABSTRACT

This investigation was concerned with mechanical damage to corn caused during the pneumatic conveying used extensively in commercial channels.

Conveying air velocity, repeated runs, moisture content, and size and/or shapes of corn were studied to investigate the effects on the extent of mechanical damage such as dockage, broken kernels, small and large cracks. A total of 200 feet of conveying length, consisting of horizontal and vertical pipes of 1.9 inches ID and connected by 15 elbows, was used in the conveying system.

The results showed that higher conveying velocity, especially with increased repeated runs, was the most important cause in each classification of damage. These effects were more pronounced at low moisture level (12 percent) than at high moisture (about 20 percent on wet basis).

Size and/or shapes of corn studied responded differently to each of the damage components and were statistically significant, even though the effect was, in most cases, relatively small compared to the other factors studied.

Total damage rate with respect to conveying length was very high in the initial stage regardless of moisture content and of size and/or shape of corn.

In order to avoid high damage rate, especially in low moisture level (12%), it may be necessary to keep air velocity below 90 feet per second. However, for high moisture corn (12%), air velocity can be kept high for conveying even considerably

longer without causing extensive damage to corn.

The correlation between devaluation number of total damage and dockage was unsuccessful because of wide variation of the devaluation number for a given dockage. However, the following equations, relating the broken damage to dockage within a range of the system operation that might be practically encountered, were obtained:

$$B = 12.85 + 2.88 \log_e D \qquad D < 4\%$$

$$B = -18.49 + 29.23 \log_e D \qquad D > 4\%$$

These equations can be useful for predicting broken damage caused in pneumatic conveying, simply by testing samples in a dockage tester.